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REPEATED WATER ENTRY SHOCKS ON HIGH-SPEED PLANING BOATS

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The occupants of high-speed planing boats (HSPBs) are exposed to repeated shock impacts that result from hull slamming during operations in rough water. The development and application of injury/performance prediction methods and standards to HSPB operation are discussed. Tests conducted at sea to quantify repeated shocks are described and results are presented. The applicability of scale model tests and the development of computer simulations are discussed. Relationships between test data and existing and proposed standards and models for injury potential are discussed. Recommendations for additional testing and development are presented.

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FOREWORD

The occupants of high-speed planing boats (HSPBs) are exposed to repeated shock impacts that result from hull slamming during operations in rough water. The development and application of injury/performance prediction methods and standards to HSPB operation are discussed. Tests conducted at sea to quantify repeated shocks are described and results are presented.

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INTRODUCTION

This report documents the second and part of the third year of effort within the four-year Coastal Systems Station (CSS) High Speed Planing Boat (HSPB) shock mitigation investigation. The first year, fiscal year (FY) 1993, included the technology assessment of existing shock mitigation techniques, and initial testing at sea. The FY 1994 and FY 1995 effort reported here included additional acceleration tests at sea to quantify exposure to repeated shocks during HSPB operation, evaluation of existing data and theory relevant to water-entry and planing boat dynamics and human dynamics and injury, and development of computer models for predicting potential for discomfort and injury. Follow-on effort during the remainder of FY 1995 and FY 1996 includes laboratory drop tests for model validation, application of the model to the identification and development of shock mitigation concepts, and construction and at-sea demonstration.

BACKGROUND

In 1989, CSS conceived the variable deadrise hull (VDH) to increase the speed of planing boats at sea by enabling the crew to optimize the shape of the hull according to the encountered sea state. Investigation of the applicability of the VDH concept to HSPBs indicated the VDH could mitigate the repeated shocks in waves. The focus of the VDH project was then modified to take advantage of the inherent shock mitigation potential of the variable deadrise concept.

CSS measured shock loads on operational planing boats as part of a National Medical Research Institute study to quantify the shock environment and medical effects associated with operating the boats. Using those measurements as input, a detailed design for installing a VDH system on a half-scale boat was completed. The VDH system was installed, and preliminary tests were conducted in FY 1991. Design modifications based on the preliminary tests were made to the half-scale boat, and a preliminary comparative test was conducted in February 1992 between the half-scale boat and a boat of fixed deadrise. At-sea Mechanical Impactograph data demonstrated reduced accelerations in the VDH boat.

Later in 1992, CSS refined the VDH design, and fabricated a new prototype VDH for the half-scale boat. Side-by-side testing of the new VDH boat and a fixed deadrise baseline boat was conducted in September 1992 to measure and analyze the shocks on the planing hulls to more accurately quantify the shock mitigation effectiveness of the VDH. The test indicated a significant shock mitigation capability of the VDH.

In FY 1993, CSS expanded the VDH development effort into the HSPB Shock Mitigation program, as part of the Office of Naval Research Technology Base Program. The program was organized according to the following objectives.

1. Assess existing technology applicable to planing boat shock mitigation
2. Characterize the repeated shock environment with at-sea data
3. Investigate applicable hydrodynamic impact theory
4. Identify existing prediction methods and standards for human injury and performance
5. Develop drop/injury computer models and validate with drop tests
6. Evaluate candidate designs with drop/injury model
7. Design, construct, and evaluate model and full-scale concepts at sea

The first objective, the technology assessment, was completed in FY 1993 and documented separately.[1] This report documents the second through fifth objectives, completed in 1995.

Application of the computer models to the evaluation and development of candidate designs, and tests of components and subsystems were conducted in early 1995. Prototype designs were initiated later in FY 1995, and construction and at-sea evaluation will be conducted in FY 1996.

REPEATED SHOCK DEFINITIONS

Distinctions can be made between impacts, impulses, impulsive forces, and pulses. Mechanical engineering texts[2,3] and handbooks[4] refer to an impact as a short duration collision event and to an impulse as a time integral of force. Although the impulse definition does not limit frequency content or the time interval over which the impulse is integrated, impacts and impulses are usually described as broadband and short duration events. Ideal impulses are represented as functions that approach infinite magnitude and zero duration.[5] The term pulse implies a finite duration of time over which the pulse occurs. Shock time histories are often called shock pulses. Impulsive forces are typically defined as large magnitude forces that act over a short period of time.[2]

For this investigation, the initial collision event of a boat with the water surface may be referred to as an impact or more appropriately as a shock event. Shocks, like impulsive forces, are often described in terms of relatively high amplitudes and short durations. Shocks are more completely defined as individual events that disrupt the internal equilibrium of a system through a suddenly applied impulsive force. Shocks are separate distinguishable events; vibrations are periodic. Water entry of an airborne planing boat or portion of a ship hull is often called a *slam*. Forces generated from water-entry shocks are impulsive forces. The individual shocks are non-stationary and transient. Each water-entry shock is a sudden dynamic disturbance of the boat by an applied impulsive force during a water-entry impact event. The shocks are called repeated shocks because distinguishable shocks are repeatedly encountered at sea.

The concern of this report is more for operationally-encountered repeated shocks, and less for vibrations that result from engine operation and periodic seakeeping motions. For boats larger and heavier than HSPBs some overlap may exist in the frequency ranges of vibration and shock at certain speeds and sea states. The amplitudes and durations of the HSPB shocks are usually different from those of the vibrations; thus the shocks can generally be separated and quantified. Precise numerical delineations between vibrations and shocks do not exist. For this report, shocks are defined to be distinct acceleration events resulting from water entry of some portion of the HSPB hull that are greater than 2 g in peak amplitude and have a duration (pulse width) between 20 and 200 msec.

Two methods were considered for defining the durations, which can also be called the pulse widths, of the shocks. The first method, from American Society for Testing Materials (ASTM) D 3332-88,[6] defines the rise time as the time interval required for the leading edge of a shock to rise from 10 percent of the peak amplitude to the peak amplitude, the fall time as the time required for the trailing edge of the shock to fall from the peak amplitude to 10 percent of the peak amplitude, and the duration as the sum of the rise time and the fall time. These terms are illustrated in Figure 1 (please note that all figures and tables are found at the end of this report). This duration corresponds to approximately one-half the period of a sinusoidal time history, and the frequency of the shock is the inverse of twice the shock duration. This method is commonly used to describe mechanical shocks.

The second method uses the concept of equivalent area. Referring to Figure 1, the velocity at point 2 is the maximum velocity, V_m, equal to the sum of the velocity at point 1 and the area under the curve. Setting the initial velocity to zero, the duration may be defined as the amount of time that is multiplied by the maximum acceleration, A_m, to yield the area under the curve. So, by this method, the duration is the maximum velocity, V_m, at point 2, divided by the maximum acceleration, A_m. This method is commonly used with standards and models relating mechanical shocks to injury potential.

METHODOLOGY

Previous and existing programs related to repeated shock measurements and water-entry modeling were investigated to prevent duplication of effort. HSPB crew members were interviewed to determine their perceptions and concerns about repeated shocks. Acceleration data were collected from various HSPBs operating over a broad range of speeds and sea conditions. The operator inputs and at-sea data were combined to describe the operating environment of the HSPBs. Existing theories for predicting water-entry phenomena were assessed for incorporation into a water-entry simulation. Standards and models for standing-human injury and performance were investigated. A model based on water-entry theory and injury prediction methods was developed to simulate the vertical drop, water-entry, and associated potential for injury of a two-dimensional (2-D) elastic human/boat system.

PREVIOUS AND ONGOING PROGRAMS RELATED TO SHOCK MEASUREMENTS AND MODELING

Understanding the shock and vibration levels and their effects on human beings is critical to the designers of all vehicles that carry people. Many investigations have been published concerning ships, boats, automobiles, trains, aircraft, and spacecraft.

Relevant investigations reported in the literature include those related to

- Early seaplane float water entry
- Water entry of ship-launched lifeboats, air-launched boats, and torpedoes
- Ship seakeeping and slamming
- Planing boat seakeeping and slamming
- High-speed aircraft seat-ejection impacts
- Army ground vehicle impacts
- Spacecraft water entry
- Related topics such as seat/bolsters, shipboard machinery damping, and automobile passenger comfort

Most of these investigations included some combination of numerical and theoretical analysis, model-scale laboratory testing, and full-scale testing.

von Karman, concerned with the forces on seaplane floats during landing, published an important early analysis of 2-D wedge water-entry theory.[7] Wagner later extended von Karman's theory to include spray and forward motion effects.[8] In the years since, many investigators have studied 2-D water-entry phenomena, but the von Karman and Wagner theories are often referenced and used to predict the forces on simple 2-D wedges.

The United States Coast Guard (USCG) has investigated sea-state-imparted shocks on their platforms. Accelerometers were used in separate studies to measure slamming on the prototype 47-ft motor lifeboat[9] and the Island Class patrol boat.[10] The primary purpose of each study was to verify the structural design and integrity of the craft when subjected to slamming loads. The USCG also performed seakeeping and vertical acceleration tests on their 110-ft surface effect ships[11] and compared measured accelerations to International Standards Organization (ISO) standards. Recent studies have been made of slamming and vibrational loads on large commercial ships.[12] The Naval Biodynamics Laboratory conducted a study to simulate the response of crew seating on large ships to underwater explosive shock.[13] An analysis of the ride quality of the landing craft air cushion vessel was completed at CSS in 1989.[14]

The most relevant information concerning the shock environment of HSPBs however can be found in laboratory and at-sea studies of planing hulls. These investigations may be classified according to two basic objectives. The first type includes tests that primarily measure hull pressures and are concerned with the structural ability of the hull to withstand slamming in extreme conditions.[15,16,17] The second type includes tests that primarily measure accelerations and

are concerned with the ride quality and seakeeping characteristics of the boat in moderate conditions.[18,19,20,21] Acceleration data are the most useful for this shock mitigation study, but the seaway conditions and speeds of most of the seakeeping acceleration measurements are moderate and seldom include slamming.

Laboratory drop tests have been conducted to experimentally simulate shocks by suspending and releasing a model above a water surface. Upon release, the model free falls to attain the desired velocity before entering the water. Accelerometers and/or pressure sensors on the model measure the response of the model to the water entry. Most model tests of this type involved drops of either a scale model of the entire hull or a scale model of a longitudinal segment of the hull. Drop tests of scale models of entire hulls have been conducted for small lifeboats,[22,23] and for large ships.[24] Drop tests of scale models of longitudinal sections of hulls have also been made for large ships.[25,26,27] Drop tests of both scale models of entire HSPB hulls and full-scale models of longitudinal HSPB hull segments have been conducted at CSS in 1995 in support of the shock mitigation effort documented in this report. The CSS drop tests are documented in a separate report.[28]

Studies of damping shipboard machinery vibrations, and studies of crash impacts incurred by automobile and airplane passengers are numerous. Related information can be found in proceedings from symposia on shock and vibration and in reports concerning the development and testing of other shock mitigation applications.

Investigations of hydrodynamic damping have been conducted for the offshore oil industry that are primarily concerned with damping the motions of offshore structures and marine risers. These applications are quite different from HSPBs, but many of the concepts considered for hydrodynamic absorbers, such as baffles, material selection, and layering and frequency tuning of fluids, can also be considered for HSPB shock mitigation.

A study was conducted for the manned air-launched raiding craft (MALRC) that is applicable to HSPB shock mitigation.[29] The investigation included laboratory water-entry tests of a scale-model of the MALRC hull. The resulting experimental acceleration data was used to estimate the potential for injury based on the injury prediction method of Brinkley.[30]

Two Fortran computer simulations were developed in support of the CSS VDH development effort. The simulations model the vertical water entry of the VDH with inner and outer hulls separated by air bladders. One version models the linear response of the boat, and the other models the nonlinear response. A three-dimensional, finite-element model, written in Abacus, was also developed. A more complete discussion of these simulations is included in Reference 1.

Shock mitigation methods are ultimately meant to increase operational effectiveness by reducing potential for injury, and by maintaining or improving the performance of the boat occupants. Several standards related to human exposure to vibration have evolved during the past 20 years. The standard most often referenced in the literature is ISO 2631,[31] but this early standard is inappropriate for either repeated or isolated shocks on HSPBs. More recent standards

have evolved for vibration mixed with repeated shock. One of these, the British Standard 6841,[32] is marginally applicable to planing boat water-entry shocks. British Standard 6841 primarily considers human performance degradation in the presence of repeated shock combined with vibration. The standard is not well suited for immediate or long-term injury from isolated or repeating shocks, and does not distinguish between seated and standing humans.

Several methods for predicting injury from severe isolated shocks are reported in the literature. These methods have not been accepted as formal standards, partly because the methods are based on scarce data. One class of such methods includes what may be called *acceleration-duration* methods that are based on waveform analysis of an individual acceleration time history. The incidence of injury or effect on performance is correlated with acceleration waveform characteristics. Examples include the methods of Glaister[33] and Hirsch.[34] Another class of methods may be referred to as *displacement-response* methods. These methods use an established human biodynamics model to predict the maximum displacement of the central portion of the seated human body during a vertical shock. The human model is driven with a predicted or measured seat kinematics time history, and the resulting maximum displacement is correlated with the probability of injury. References 30, 35, and 36 are examples of studies concerning displacement-response methods. Further discussion of injury modeling methods is included in a later section of this report.

The U. S. Army Aeromedical Research Laboratory in Fort Rucker, Alabama is conducting a multi-year program concerning the effects of repeated shocks on the operators of tanks and other ground vehicles. The overall goal of the program is to develop a new standard for exposure to repeated shock in army vehicles. Specific objectives are to (1) identify the adverse health effects,[37] (2) compile existing ground vehicle acceleration data, and process the data with existing and proposed methods,[38] (3) measure the physiological responses of the human subjects under simulated conditions, and (4) using results from the first three objectives, establish a new standard for processing kinematic data and correlating the processed results with the incidence of health effects. Much of the effort was contracted to the British Columbia Research Incorporated (BCRI). To date, the first two phases have been completed, and the second two phases are underway. Development of shock mitigation methods is not included in the scope of the effort. An essential difference between the army applications and the HSPB applications is that army personnel are usually seated in their vehicles during operations, and personnel often stand during HSPB operations.

Coordination of the HSPB shock mitigation program is continuing with the MK V Special Operations Craft program, with programs involving other surface platforms, and with naval special warfare medical studies.

Additional information concerning seakeeping tests, drop tests, and full-scale tests related to methods for mitigating shock loads is included in Reference 1, the technology assessment in support of the HSPB Shock Mitigation program.

TESTING AT SEA

Acceleration measurements of HSPBs at sea were made during 1991, 1992, 1993, and 1994. Test method and instrumentation verification tests were conducted in August 1991 off Norfolk, Virginia. Test data were taken during August 1991, April and June 1992, and March 1994 off Norfolk, Virginia, and during September 1992 and August 1993 off Panama City, Florida. Data were also taken for short and long duration transits during May and July 1992 off the East Coast of the continental United States and Puerto Rico.

OCCUPANT INPUTS

The primary concerns expressed by boat occupants subjected to repeated shocks are related to discomfort, pain, and decreased on-site mission effectiveness. The occupants also express concerns about damage to the boat and payload.

Some of the boat occupants view the pay-off of shock mitigation research more as increased speed for the same level of discomfort than as decreased discomfort for the same speed. They also feel strongly that shock mitigation systems should not be used at the expense of payload capacity and other important mission capabilities. Overall mission effectiveness must not be reduced.

Boat occupants also do not want to be completely isolated from the environment. They want to be able to feel the sea conditions and the responses of the boat to the seaway and to their speed and maneuvering controls.

For this investigation, the word *isolation* is used in the mechanical engineering sense and is not meant to imply that personnel could or should be completely isolated from the environment. Complete isolation might be desirable for a specific scenario such as transport of a severely injured passenger or delicate equipment. For such cases, a dedicated, case-specific module could be installed on the boat.

INSTRUMENTATION AND DATA COLLECTION

Investigators of planing boat dynamics often measure hull pressures because they provide indications of hull performance, and because hull pressures are essential inputs for the hull design process. Investigators of shock and vibration typically measure accelerations. Accelerometers were used for this study because the primary objective was to characterize the shocks imparted to the boat and boat occupants.

Selection of accelerometers requires a trade-off among range, frequency response, weight, size, and expense. Piezoelectric accelerometers are dynamic accelerometers with frequency response limited according to the discharge time constants of their electrical circuits. Piezoresistive accelerometers can accurately measure very low frequency phenomena, but their accuracy and survivability can be easily diminished by the operating environment. Both

piezoelectric and piezoresistive accelerometers were used for this investigation to measure the full range of accelerations and the full frequency response. Hermetically sealed accelerometers were chosen for resistance to the harmful effects of the test environment.

For analog data acquisition, the signals from the accelerometers are amplified, filtered, or otherwise conditioned prior to storing them on analog tape. This method has several advantages. A complete time history of shock events and the time between events is captured. The stored data tape can be replayed for analysis with varying sample rates and filtering methods. Unfortunately, most analog tape drives are large, heavy, and expensive, and many cannot withstand the extreme HSPB shocks and the marine environment. For these reasons, digital collection devices were chosen to sample and collect the signals from the accelerometers on the HSPBs at sea.

The analog voltage signals from the accelerometers were transmitted by hard wire to the data collection units. The data collection units multiplexed the signals, converted the analog signals to digital values, and stored or passed the digital values to computers for storage. Peak acceleration loggers were also used during some data runs.

Boat speed and heading for the verification tests and the long duration tests were measured with a TrimPack Global Positioning System. Speed and heading for the tests conducted off Panama City were measured with an Ensign Model receiving and display unit manufactured by Trimble Navigation.

The boats were instrumented and test runs were made in various directions in various sea states at various speeds. On each test day, all instruments were time-correlated before the boats were deployed. During the test runs, the collected data were stored in compressed form. The data were downloaded to removable disks after each test run. Preliminary examinations of the run data were made daily, and more extensive analyses were conducted after testing was concluded. Handwritten test logs were used to record test times, boat speeds, directions of seas, and other test conditions. Videotape records and still photographs were taken during some test runs.

The raw data in compressed format were transferred from the removable disks to a desktop personal computer. These files were converted to ASCII format files, and some were low-pass filtered for specific frequencies. The ASCII files were rearranged by Fortran program into the format required for importing the data into the "DADiSP" program for data display and analysis. "DADiSP" software was used for frequency domain analysis and plotting.

VERIFICATION OF INSTRUMENTATION AND DATA COLLECTION

Confidence in the accuracy of the portable instrumentation used to measure the repeated shocks on the HSPBs was initially based on favorable comparisons of the recorded data to the way the boats felt to the occupants. More objective verification was sought by comparing the CSS instrumentation to other digital systems and to an analog data recording system.

Two tests were conducted that successfully verified the digital piezoelectric instrumentation and procedures used by CSS to collect shock data. The first test was conducted in June 1992. Instruments from CSS and Oak Ridge National Laboratory, Tennessee, were tested side by side on HSPBs operating off Norfolk, Virginia.

The second verification test was conducted during the week of August 18, 1993. Instruments from CSS and from the Airborne and Special Operations Test Directorate (Airborne Board) were placed side by side on the decks of three planing hulls. The boats were operated over small seas and boat wakes in St. Andrew Bay, Florida, and data characterizing the response of the boats were recorded and analyzed. The CSS data were recorded digitally onboard the boats, and the Airborne Board data were collected on a shore-side analog tape recorder from signals transmitted by radio link from the boats. The signals were also recorded on a shore-side strip chart recorder.

Time-domain and frequency-domain analyses from both tests indicated excellent agreement of the collected data.

INITIAL EVALUATION OF HSPBs

Peak accelerations and acceleration time histories were recorded on operational boats during 1991 and 1992 in various sea states at various locations in the Atlantic Ocean. Most of the measured shock amplitudes were between 2 and 10 g, but some were greater than 10 g. These data will not be discussed further because the boats that were tested in 1991 and 1992 were significantly different from the boats that have superseded them.

MARCH 1994 AT-SEA TESTS

Accelerations were measured on HSPBs in the Atlantic Ocean in March 1994. The boats are about 40 ft long over all, and are foam and fiber-reinforced plastic sandwich construction. Testing was conducted as a joint effort by CSS, the Navy Surface Warfare Center Combatant Craft Division, Metron Incorporated, the Naval Research Laboratory, and active duty Navy personnel. Accelerometers were placed on a stainless steel plate secured to the cockpit deck at the longitudinal centerline of the boat, 11-7/8 in. forward of the longitudinal center of gravity (LCG) of the boat. Accelerometers were mounted at that location rather than exactly at the LCG because occupants stand at that position during transits, and because the mounting plate at that location was rigidly attached through the deck to the centerline longitudinal of the boat, permitting more accurate measurements than could be made at the less supported deck area at the LCG. Accelerometers were also mounted in the forward compartment of the boat 18 ft 3 in. forward of the LCG. Lightly and heavily loaded boats were tested side-by-side.

Instrumentation

Both piezoelectric and piezoresistive accelerometers were used to measure the full range of accelerations and the full frequency response. The piezoelectric accelerometers installed on the boats were all low impedance quartz crystal and seismic mass instruments of the Model 3100 series as designated by the manufacturer, Dytran Instruments, Incorporated, Chatsworth, CA. The nominal sensitivity of the accelerometers was 50 mV/g with a range of ±100 g. Low frequency response was 1 Hz ±10 percent at 5 percent down. All were calibrated with traceability to the National Institute of Standards and Technology. The accelerometers were secured in the longitudinal, transverse, and vertical directions to solid aluminum mounting blocks.

The signals from the piezoelectric accelerometers were sampled at 2111 samples/sec and collected by interface units designated IS-4's by their manufacturer, Dallas Instruments Incorporated in Dallas, Texas. The analog voltage signals from the accelerometers were transmitted by hard wire to the IS-4. The IS-4 is a four channel multiplexor that converts the analog voltages to 12-bit digital values, and transmits them by RS-232 cable to a laptop computer for storage. The software for the IS-4, loaded into the computer, was used to drive the data collection and storage to computer memory. The IS-4's and the laptop computers were packed in lightweight, padded, and waterproof cases that were secured to the test boat. Collected data were written to virtual memory to save sampling time and to avoid possible loss of data on the hard disk.

The piezoresistive accelerometers were factory-mounted in the longitudinal, transverse, and vertical directions inside the analog-to-digital interface units manufactured by Instrumented Sensor Technology Incorporated (IST), in Okemos, Michigan. The acceleration range of these accelerometers was ±50 g, and the frequency range from direct current to 510 Hz. These accelerometers were sampled at 1024 samples/sec and the signals were collected and stored at 10-bit resolution by the IST units.

Since the primary purpose of this study was to characterize the shocks, and since the memory capacities in the collection and storage devices were limited, the devices were set to record data only after being triggered by an acceleration greater than 2 g. If any of the accelerometers measured a shock in excess of 2 g, the data from all the accelerometers for that shock were recorded for a specified amount of time before and after the shock. Recording data in this manner does not provide a continuous time history, but it does provide an efficient method for recording complete time histories of the shock events of interest.

The peak acceleration loggers installed on the boats were designated *PALs* by their manufacturer, Dallas Instruments Incorporated. The *PALs* are stand-alone units that contain accelerometers that measured accelerations in the vertical, longitudinal, and transverse axes. Data loggers in the *PALs* recorded the peak acceleration encountered for each axis each second. After test runs were completed, the data from the *PALs* were downloaded to a personal computer via RS-232 interface. *PALs* were used as a check for the acceleration levels measured by the other systems.

At-Sea Test Results

The following paragraphs describe the characteristics of the shocks as measured during the March 1994 at-sea tests. All accelerometers used for these tests measured 0 g when at rest. All reported accelerations are referenced to 0 g for the craft floating in static equilibrium.

Results Measured With Piezoresistive Accelerometers. Figure 2 shows two complete shock events and most of a third shock event from an unfiltered vertical time history recorded onboard an HSPB operating near cruising speed in 3-ft swells with 2-ft chop in 20-kt winds. The unfiltered data indicates high frequency signal components carried over the basic shock. A ring test of the box that enclosed the accelerometers indicated the fundamental frequency of the box to be 104 Hz. Low-pass filtering of the data at 25 Hz produces the acceleration time history shown in Figure 3.

Three distinct phases of the individual shock event centered at about 2.2 sec can be seen in Figure 3—the free-fall phase, the water-entry shock phase, and the recovery phase. Upon launching off a wave, the boat became airborne and began to free-fall back toward the water surface. During the free-fall phase, the only force applied to the boat, other than a negligible amount of air resistance, was gravitational; therefore, in the absence of rotation, the time history should remain at -1 g until the boat re-enters the water. The free-fall phase continues for about 0.5 sec for the events shown in Figures 2 and 3.

The second phase is the water-entry shock pulse, which is shown in the time history by the rapid rise from -1 g up to the peak amplitude and the subsequent fall back toward 0 g. During this phase, the vertical fall of the boat is rapidly decelerated by a combination of the wedge entry and the planing lift of the hull. The rise time is about 65 msec and the fall time is about 80 msec, for a total duration of the water-entry phase of about 145 msec.

The third phase is the recovery, which includes the partial submergence and subsequent emergence of the hull following the water-entry impact. For the event shown in Figure 3 at 2.2 sec, the duration of this phase is about 500 msec. The duration of this phase varies significantly depending on the attitude of the boat when it enters the water.

The relative contributions of the forces that determine the three phases of the acceleration time history are discussed in more detail in the section of this report that describes the CSS water-entry simulation.

The other two events shown in Figure 3 indicate combinations of lower amplitude shocks preceding larger amplitude shocks. These are time histories of events where the after part of the hull initially entered the water at a bow-up angle of pitch, and the rest of the hull subsequently rotated into the water. This can be a preferred method of water entry because the vertical velocity of the falling boat is diminished over a longer period of time through two lower amplitude shocks rather than one higher amplitude shock.

Results Measured With Piezoelectric Accelerometers. Figure 4 shows an unfiltered vertical time history from one of the more severe shocks recorded with a piezoelectric accelerometer onboard a boat that included hull strakes, operating between cruising and full speed in 2-ft swells with 1.5-ft chop in 11-kt winds. Again, high frequency signal components are carried over the basic shock time history. Filtering the data at 100 Hz produced the time history shown in Figure 5.

Figure 5 shows a pair of peaks within the water-entry impact that were initially believed to result from either succeeding entries of the strakes into the water, or the natural frequency of some portion of the boat structure. An examination of the geometry of the strakes and the estimated boat velocity at water entry indicates that the spikes in the time history were the result of the strakes. While the strakes may appreciably affect the nature of the shock time histories, and drop tests indicate that strakes shorten the duration of the shocks, the effects of the strakes are primarily at frequencies greater than those injurious to people.

Filtering the data at 30 Hz removes extraneous components of the time history, leaving only the shock time history as shown in Figure 6. Low-pass filtering reduces the peak amplitudes depending on the high frequency contributions to the overall time history. The peak of 20 g shown in Figure 4 is reduced to 5 g in Figure 6; the 5-g peak is more properly representative of the lower frequency component of shocks that cause discomfort and injury. The shock durations are not significantly affected by filtering.

For this report, the HSPB acceleration time histories will generally be filtered at 50 Hz for the following reasons. Filtering is necessary to avoid contamination from the measurement device mounting system. Further, the human body is less sensitive to high frequency components of shock events. The spine is most sensitive to frequencies of 15 Hz or less. Bones in the ankles and legs are most affected in the 10- to 30-Hz range. Figure 7 shows the event filtered at 50 Hz.

The inability of the piezoelectric accelerometer collection system to collect low frequency data is shown in Figures 4, 5, 6, and 7. During the free-fall phase prior to the water-entry impact, the acceleration should be -1 g, but the recorded time history decayed exponentially toward 0 g because the signals from the piezoelectric accelerometers decay exponentially when there is no change in acceleration. The nominal discharge time constant of the piezoelectric accelerometers was 1 sec, but the coupling capacitance in the IS-4's further limited the 5 percent down, ± 5 percent low-frequency response to about 5.6 Hz. The water-entry impact phase occurs rapidly enough for the magnitude and the duration of the rise to be accurately measured, but the magnitude is offset by 1 g. The rise actually began at -1 g, not 0 g, and the peak amplitude was actually 5 g, not 6 g. This offset was verified by measuring triangle and square wave signals input into the data collection system. The initial decrease in acceleration from the peak occurs rapidly enough to be accurately measured except that the actual fall from the peak begins at 5 g rather than 6 g.

The buoyancy and drag forces of the recovery phase occur too slowly to be measured by piezoelectric accelerometers. The time history in Figure 7 continues to decrease past 0 g to -1.7 g. Water-entry simulations and piezoresistive data show that the acceleration during the recovery phase should be nominally 1 to 2 g. Piezoelectric accelerometer values of less than

0 g during the recovery phase could possibly have been caused by structural elastic effects within the boat hull and deck in response to the water-entry shock, and/or by the accelerometer capacitor discharge after excitation during the shock pulse. The triangle and square wave tests determined that the negative acceleration was in fact an electrical overshoot. Typical recovery phases are shown in Figures 2 and 3.

Comparison of the time histories measured with piezoresistive accelerometers to those measured with piezoelectric accelerometers indicate that piezoelectric accelerometers are capable of measuring the water-entry impact phase. Since this phase is more important to most investigators of HSPB shocks, the more rugged piezoelectric accelerometers can often be recommended, but other accelerometers and data transmission methods are required to measure the lower frequency characteristics of the recovery phase.

The shock event shown in Figures 4 through 7 was one of the more severe impacts measured during that data run. The data collection equipment was set to trigger at 2 g, and 339 shocks were recorded. During the tests, the measured magnitudes of the shocks were consistently greater at the bow than at the crew stations, and greater at the crew stations than further aft.

Figure 8 shows an unfiltered piezoelectric vertical acceleration time history recorded during the March 1994 tests. The figure shows a typical sequence of repeated shocks occurring approximately 1.1 sec apart. For the March 1994 tests, the time interval between events was between 1 and 2 sec. The time interval shown in Figure 2 was approximately 1.7 sec. The time interval can be shorter or longer than 1 sec depending on boat speed and sea state.

AT-SEA TEST CONCLUSIONS

As expected, the measured HSPB vertical acceleration magnitudes are substantially greater than those reported in Reference 12 for a heavier craft operating in smaller seas at lower speeds, and also greater than those reported in Reference 11 for a heavier craft operating at slower speeds in comparable or greater sea states. It is generally believed that lighter planing boats (and semi-displacement boats) incur shocks of greater amplitude than heavier boats of the same geometry, and that shock amplitudes increase with increasing boat speed.[11] These trends were qualitatively verified during the at-sea acceleration tests, and agree with laboratory drop test results and water-entry simulations.[39]

The data qualitatively agree with descriptions given by boat occupants of the relative magnitudes of the directional components of the shocks. Examination of the data from all the tests showed that the acceleration magnitudes are much lower in the longitudinal and lateral directions (on the order of 10 percent) than in the vertical direction. Occupants usually stand during HSPB rough water operations, to use their legs to mitigate vertical shocks. Occasionally the bow of the boat would plunge into an oncoming wave, producing a predominantly longitudinal acceleration. If the boat is rolled or pitched at the time of a shock, occupants are exposed to accelerations containing transverse and/or longitudinal components in addition to the vertical. In some specific incidents, such as the sudden rolling of the boat from chine to chine, non-vertical accelerations are dominant and of significant magnitude to be of concern.

INJURY AND PERFORMANCE ASSESSMENT

HSPB water-entry shocks can produce discomfort, impair performance, and in extreme conditions, cause injuries. The objective of this section is to identify and apply appropriate existing prediction methods and standards for assessing the potential for discomfort, performance loss, and injury based on the kinematics of the human or the structure on which the human body is standing or seated. These kinematic data may be obtained from simulations, scale model laboratory tests, or full-scale tests at sea. Later in the shock mitigation effort, the CSS water-entry simulation, including the appropriate injury prediction model, will be used to evaluate proposed shock mitigation concepts.

Types of occupant debilitation related to repeated shocks include (1) en-route and on-arrival performance degradation produced by shock-related fatigue and discomfort, (2) chronic injuries from severe shocks or repeated moderate shocks, and (3) acute injuries from severe isolated shocks. Examples of debilitation, approximately in order of increasing severity, include annoyance, fatigue, sleepiness, discomfort, anxiety, nausea, loss of visual acuity and hand-eye coordination, abdominal pain or discomfort, testicular pain, headache and other head symptoms, chest pain, back pain, sprains, torn ligaments, broken ankles and legs, damaged vertebrae, and damage to internal organs.

A brief summary of the evolution of discomfort/injury prediction methods and standards related to vibration, repeated shocks, and individual shocks follows. Standards and methods are recommended for processing HSPB kinematic data to assess the probability of discomfort and, where possible, the probability of injury.

EARLY VIBRATION-ONLY METHODS AND STANDARDS

Griffin[40] published a frequently referenced handbook on vibration affects on humans that includes a comprehensive description of the early and evolving standards. Early methods for assessing the level of discomfort, fatigue, annoyance, and motion sickness from kinematic data are outlined in four ISO standards.[41] These standards were superseded in the 1980s by the well known ISO 2631 Parts 1, 2, and 3.[31] ISO 2631 Parts 1 and 3, for assessing the effects of periodic motion on humans, are sometimes used to assess human discomfort and performance effects of moderate-amplitude periodic seakeeping motions; however, these two standards do not assess the possibility of discomfort or injury from isolated or repeated shocks.

ISO 2631 Part 1 predicts discomfort and *fatigued-decreased deficiency* from harmonic and random vibration. This standard considers transmission of vibration into the body from all three directions. In the vertical direction, the standard does not distinguish between the seated and standing positions. This standard also does not address the effects of significant levels of shock within the vibration time history.

For humans, the most sensitive vibration frequency range for producing fatigue and discomfort in seated or standing subjects is from 4 to 8 Hz along the body length and below 2 Hz for accelerations in the two transverse directions relative to the longitudinal body axis.

Figures 9 and 10, from ISO 2631 Part 1, illustrate the guidelines. Figure 9 is applicable to exposure along the length of the body, and Figure 10 is for transverse exposure. These figures show that the duration of exposure is an important parameter for determining the tolerable level of acceleration. The contours represent the root mean square (RMS) of the acceleration, within 1/3-octave bands, above which fatigue and discomfort produce a significant reduction in proficiency. An extreme exposure boundary is defined by multiplying the acceleration values by 2, and a reduced comfort boundary is defined by dividing the acceleration values by 3.15.

The method for assessing fatigue/discomfort potential, as outlined in ISO 2631 Part 1, is to record the unfiltered, 3-axis acceleration time history of the surface on which the human is standing or firmly seated, compute the RMS of the accelerations in 1/3-octave bands, and use Figures 9 and 10 to assess the possibility of reduced proficiency from fatigue and discomfort based on exposure duration. The roll-off in the figures reflects the ability of the human body to filter the motion. Alternatively, weighting values are prescribed in the standard for each 1/3-octave band, which may be applied to the raw acceleration time history, reproducing the roll-off in Figures 9 and 10.

ISO 2631 Part 2 is for assessing annoyance from low level vibration, as might be experienced in buildings, and is not directly relevant to the present investigation.

ISO 2631 Part 3 is for assessing the possibility of motion sickness resulting from low-frequency periodic vibration. Care must be taken during the development of shock isolation methods to avoid shifting energy into the lower frequency motion sickness domain.

Figure 11 shows the contours of RMS acceleration for varying exposure times above which reduced proficiency from motion sickness is expected. The method for assessing the possibility of reduced proficiency resulting from motion sickness is identical to that given previously for fatigue and discomfort, except that Figure 11 is used instead of Figures 9 and 10.

The standards of ISO Parts 1, 2, and 3 were incorporated into MIL-STD-1472D.[42] The Marine Corp is developing a high-speed, heavily loaded planing landing craft for operation in heavy seas, called the Advanced Amphibious Assault Vehicle (AAAV). MIL-STD-1472D has been used to assess discomfort and performance loss from AAAV kinematic data.

ANALYSIS OF INDIVIDUAL AND REPEATED SHOCKS

Severe isolated or repeated shock events during HSPB operation are often immersed within a lower magnitude, periodic vibration level. In this section, methods will be summarized for assessing the effects of isolated or repeating shocks, neglecting the presence of the lower level seakeeping vibration. In a later section, standards will be described, which have been recently developed to assess repeating shocks mixed with vibration. Hirsch[34] gives an excellent summary of the effects of individual shocks on humans and a review of the early literature.

Methods that have evolved for assessing individual shocks in the absence of vibration may be categorized into displacement-response methods and acceleration-duration methods. Displacement-response methods, currently available only for seated humans, assess the possibility

of spinal injury based on the maximum displacement relative to the seat. Acceleration-duration methods are available to assess severe discomfort, based on combinations of the magnitude and duration of the acceleration of the surface on which a human is standing or seated.

Displacement-Response Method

In the 1970's, Payne[36] began to develop a method for assessing the effect of isolated shocks on the sitting human, represented as a linear biodynamic model of the human torso. For this method, the injury of primary concern is spinal damage assumed to be caused by internal spinal displacement, in the vertical direction, relative to the seat. Sufficient vertical displacement and injury data existed at the time to correlate the two.

The Dynamic Response Index (DRI) method is based on a model of the human as a linear, 1-degree-of-freedom (DOF) spring-mass-damper system

$$\ddot{\delta}(t) + 2\zeta\omega_n\dot{\delta}(t) + \omega_n^2\delta(t) = \ddot{z}(t), \tag{1}$$

where $\delta(t)$ is the displacement time history of the center of the human torso relative to the seat, ω_n and ζ are the torso's natural frequency and damping ratio, and $z(t)$ is the measured vertical displacement of the seat on which the body is firmly sitting. The values of ω_n and ζ were experimentally determined to be 52.9 rad/sec and 0.224. The maximum DRI_m is then defined as the nondimensional quantity

$$DRI_m = \omega_n^2\delta_m / g_c, \tag{2}$$

where δ_m is the maximum displacement calculated from Equation (1), and g_c is the acceleration of gravity.

The Air Standardization Coordinating Committee published the 1977 Air Standard[43] that includes the displacement-response method for assessing the possibility of spinal injury during high-performance aircraft seat ejection. The approach is to (1) measure the kinematics of a point on the seat near the human Center of Gravity (CG) (with the human firmly attached to the seat), (2) assume the human behaves as a linear spring-mass-damper system and solve Equation (1) for the maximum vertical displacement of the human CG relative to the seat, (3) compute the DRI_m according to Equation (2), and (4) relate the value to the probability of spinal injury, based on historical empirical data.

Brinkley[44] gives the maximum DRI guidelines, listed in Table 1, for assessing the probability of spinal injury to seated humans subjected to vertical shocks.

By the mid-1980's, Brinkley[35,44,45,46] was applying the displacement-response method to the analysis of isolated shocks in all three translational axes, and had also begun to consider the rotational axes. Brinkley defined the combined dynamic response ratio,

$$CDRR(t) = [(\delta_x(t)/S_x)^2 + \delta_y(t)/S_y)^2 + \delta_z(t)/S_z)^2]^{1/2} \tag{3}$$

as a three-axis application of the displacement-response concept, where δ denotes the calculated time-dependent displacements and S denotes the maximum permissible displacements.

Boef included an application of the displacement-response method with a strip-theory model of the water-impact loading on a lifeboat, leading to a prediction of the kinematics of the seated human torso within the passenger compartment.[22,23] Boef then applied the 3-axis Payne/Brinkley method, Equations (1) through (3), to predict the probability of injury. Table 2 lists the values of the natural frequency and damping ratio for the three axes.[23]

Another modern application of the displacement-response method is that of Amatucci and Cole of Sandia Laboratories, Albuquerque, New Mexico.[47] The water entry of the MALRC was investigated under the FY 1991-1993 CSS Naval Special Warfare 6.2 Technology Base Program. Amatucci and Cole measured the translational and rotational kinematics of a 1/10th-scale model with accelerometers and rate gyros, filtered the data at 20 Hz, transferred the kinematics to the passenger compartment, and applied Equations (1) through (3) in three directions using the parameters of Table 2 to assess the possibility of injury to the crew.

Acceleration-Duration Methods

An acceleration-duration method is currently required for standing subjects since a dynamic model of a standing human does not presently exist. Since acceleration-duration guidelines exist for both standing and seated humans, an acceleration-duration method may also be applied to seated humans as a check against the displacement-response method. The basic approach of acceleration-duration methods is to correlate the possibility of extreme discomfort with the magnitude and duration of the acceleration of the base on which the human is standing or seated.

Several examples of acceleration-duration methods are seen in the literature. The 1977 Air Standard was cited previously regarding application of the displacement-response method to aircraft seat ejections. The standard was also used to predict injury during the *post*-ejection phase, with an acceleration-duration method. The post-ejection phase involves aerodynamic, rocket, and parachute opening forces that produce transverse and vertical loads to the seated pilot. For the transverse directions, sufficient data did not exist, nor was a human biodynamic model for transverse impacts available to form a correlation between the DRI and injury. Thus, for the post-ejection phase, when the human was subjected to shocks in all three directions, the duration of the exposure to various acceleration levels was used to determine probability of injury.

Glaister[33] gives a similar method, shown in Figure 12, for assessing human tolerance to individual shocks. The lines within the figure represent contours of *maximum tolerable impact loading* for a standing human with legs bent, a standing human with legs straight, and a seated human. The guidelines of Figure 12 assume a rectangular acceleration waveform. Since the planing boat impact waveforms tend to be shaped more like a half-sine, some means of computing an equivalent acceleration and duration is required. Meier-Dornberg[48] provides a method where an effective duration value is computed by dividing the velocity change during the impact by the maximum acceleration. The velocity change is computed by simply integrating the area under the measured impact acceleration time history.

Meier-Dornberg also provides acceleration-duration guidelines, some of which were summarized by Griffin.[40] Hirsch[34] gives the following guidelines for lifeboat passengers in a seated condition with lap and shoulder belts. A maximum vertical acceleration of 12 g is tolerable for a duration of 100 msec in an emergency lifeboat evacuation. For a longer duration, up to 500 msec, approximately 7 g is tolerable. The Norwegian agency Det Norske Veritas[49] has proposed tolerance limits that are somewhat more conservative than those of Hirsch.

Nelson, et al.[50] argue the merits of the displacement-response method relative to the acceleration-duration methods. Advantages of the displacement-response method include the relatively large amount of data correlating the DRI to seated human spinal injuries, the ability to readily combine multiple axes into a 3-axis criterion, and the inherent computational ease of handling complex base acceleration waveforms. Disadvantages include the current limitation to seated occupants, and the requirement for an algorithm to integrate Equation (1).

Analysis of Repeated Shocks

The Air Standardization Coordinating Committee published the 1982 Air Standard[51] for assessing the potential for seated human discomfort and injury during exposure to repeated shocks. The method is based on Allen's[52,53] extensions to the original displacement-response methods of Payne and Brinkley. The method involves the measurement of individual shock time histories sustained by the seat over a 24-hour period. The DRI values are computed for each shock, and the values are grouped into a number of DRI magnitude ranges, each with a number of occurrences within that range. Each of these magnitude/number pairs are compared to a set of curves showing contours of *equi-noxious discomfort/injury*, Figure 13. The curves represent health effects ranging from *passenger comfort* to *5 percent injury with 100 day recovery.*

INTEGRATION OF VIBRATION AND REPEATED SHOCK STANDARDS

Recent ISO and British Standards Evolution

Since repeated shocks and vibration are usually present together, the ISO and the British Standards Committees worked toward development of integrated standards, allowing vibration mixed with shock to be assessed with a single ISO or British standard. The result was the British Standard 6841.[54] Later the ISO 2631 standard was modified based on the BS 6841, leading to ISO TC108/SC4 (Draft).[55] The RMS processing of the earlier standards was extended in BS 6841 to the root-mean quad (RMQ) to capture the effects of embedded, high crest-factor, repeated shocks. While injury is mentioned in the standard, the primary focus is performance degradation. The applicability of the standard to immediate or long-term injury resulting from severe isolated or even repeated shocks is questionable.

The BS 6841 defines four types of health effects and presents a data processing method for assessing the potential for each. The four health effects include (1) immediate and long-term mild injury resulting from a dose (level and duration) of vibration and repeated

shock, (2) immediate diminished ability (e.g., hand-eye coordination) resulting from a level of vibration, (3) immediate discomfort and perception-loss, resulting from a level of vibration, and (4) immediate motion sickness resulting from a level and duration of low frequency vibration.

The BS 6841 procedure includes weighting of the data in 1/3-octave bands using factors that are improved over those of ISO 2631, calculation of RMS and RMQ values within each of the 1/3-octave bands, and comparison of the resulting values to stated limits.

Army Ground Vehicle Studies

As discussed earlier, BCRI is conducting an investigation for the U.S. Army to determine the adverse health effects of army ground-vehicle vibration mixed with repeated shock. BCRI included in their studies an extensive review of existing methods for processing kinematic data for assessment of discomfort and injury.[36,37] Based on their work, the best existing methods for evaluating seated human response to ground vehicle accelerations are the British Standard 6841 to assess the potential for immediate fatigue, discomfort, and long-term mild injury resulting from vibration with repeated shock and the 1982 Air Standard for assessing the potential for immediate injury from isolated and repeating severe shocks.

RECOMMENDED APPROACH FOR ASSESSING INJURY AND PERFORMANCE LOSS

Severe Discomfort and Injury Assessment

For assessing the possibility of extreme discomfort and injury, the displacement-response method and one of the acceleration-duration methods are recommended for evaluating planing boat kinematic data. For seated occupants subjected to severe isolated shocks, the displacement-response method is well established. The 1982 Air Standard can be used to estimate long-term injury from repeated severe shock to seated occupants. Until a *standing DRI* is developed, an acceleration-duration method such as that of Glaister should be used for standing occupants.

Moderate Discomfort and Performance Loss Assessment

The possibility of discomfort and performance loss from vibration and vibration mixed with mild-to-moderate shocks, should be assessed with the British Standard 6841. This standard uses both RMS and RMQ analysis of the vibration mixed with repeated shock to assess discomfort, motion sickness, perception loss, and mild injury. While injury is mentioned in the standard, the displacement-response and acceleration-duration methods are believed superior for assessing the possibility of injury from severe shock.

WATER-ENTRY AND PLANING BOAT DYNAMICS MODELS

Numerous investigators have developed water-entry dynamic simulations and planing boat models that are applicable or suitable for modification to assess the exposure of boat occupants to shock loading during high-speed operation in heavy seas.

Examples of vertical water-entry dynamics simulations include the work of von Karman[7], Wagner,[8] Ochi,[24] Chuang,[26] Troesch and Kang,[56] Purcell et al.,[57] and Cole et al.[58] Two pilot numerical water-impact models by Gwaltney[59] and MacDonald[60] were developed in support of the FY 1993 CSS Shock Mitigation effort. In FY 1994, CSS developed a nonlinear, time-domain, 2-D water-entry model that will be described later in this section.

Examples of planing boat dynamic models that predict accelerations include those of Savitsky[61] (based on the data of Fridsma[18,19]), Savitsky and Brown,[20] Zarnick,[62] Payne,[63] Vorus,[64] and Troesch and Falzarano.[65] Further development of these codes, to include elastic boat effects, robust geometry capability, and injury modeling, is a vital step in a long-term, cost-effective planing boat shock mitigation program. Development and validation of the water-impact model within these time-domain simulations requires laboratory drop test data.[39]

During FY 1994, CSS applied the semi-empirical planing boat resistance method of Savitsky and the empirical seakeeping method of Savitsky-Brown to the HSPB shock mitigation problem. The Savitsky-Brown equations predict vertical bow and LCG acceleration statistics for seakeeping conditions during which the hull loading is essentially moderate and periodic. The method thus applies more to fatigue and discomfort, and less to isolated, extreme, and potentially injurious impacts. Fatigue and discomfort while secondary concerns within the present investigation remain as significant issues for the HSPB occupant. However, the Savitsky-Brown acceleration statistics are not in a form suitable for analysis with conventional accepted vibration analysis methods such as the ISO 2631 vibration standard.

The characteristics of the CSS time-domain, water-entry code and the CSS semi-empirical planing boat code and an example application of each to the shock mitigation problem will be summarized in the following sections.

CSS WATER-ENTRY DYNAMICS AND INJURY MODEL

In support of the FY 1994 Shock Mitigation effort, CSS developed a computer model that simulates the free-fall and water-impact dynamics of a 2-D, 3-DOF, nonlinear elastic hull/human system. The model, called the Water-Entry Dynamics and Injury Model (WEDIM), includes a post-processor for predicting human discomfort and injury.

WEDIM predicts (1) the hydrodynamic force on the hull section during the water impact, submergence, and emergence; (2) the dynamics of the boat, deck, and human; and (3) the potential for human discomfort and injury using both displacement-response and acceleration-duration methods.

Description

The boat and human system is represented as three vertically arranged masses joined by springs and dampers, as shown in Figure 14. The calculation involves simultaneous integration of three differential equations, each describing the vertical motion of a mass—the human torso/spine, the deck on which the human is seated, and the boat. The model is a 3-DOF simulation in the sense that the vertical dynamics of three masses are predicted. The model is geometrically 2-D in that a boat section is modeled with constant fore-and-aft geometry.

The three equations of motion in linear form are

$$M_h \ddot{Z}_h = C_h(\dot{Z}_d - \dot{Z}_h) + K_h(Z_d - Z_h) - F_{hg} \tag{4}$$

$$M_d \ddot{Z}_d = C_h(\dot{Z}_h - \dot{Z}_d) + K_h(Z_h - Z_d) + C_i(\dot{Z}_b - \dot{Z}_d) + K_i(Z_b - Z_d) - F_{dg} \tag{5}$$

$$M_b \ddot{Z}_b = C_i(\dot{Z}_d - \dot{Z}_b) + K_i(Z_d - Z_b) - F_{hg} + F_w \ . \tag{6}$$

In these equations, M, F, and Z denote mass, force, and vertical displacement; C and K denote the spring and damping constants; the subscript b denotes the boat; the subscripts h, d, and i denote the human, deck, and isolation material between deck and boat; and the subscripts w and g denote the water and the acceleration of gravity.

The system forcing function may be the predicted water-impact force, F_w, or a user-specified boat time history, Z_b, obtained from drop test or at-sea acceleration data. The water-impact force theory models the free-fall drop, the initial impact based on wedge-entry added mass theory, and the submergence/emergence phase based on buoyancy and drag force predictions. The wedge-entry added mass force calculation is that of von Karman,[7] whose method is limited to 2-D prismatic hull sections. The submergence/emergence calculation is semi-empirical, given the difficulty of theoretically predicting the buoyancy and drag forces during water entry.

While Equations (4) through (6) are linear, the code allows the user to input nonlinear material isolation properties to replace K_i by inputting a nonlinear stress-strain curve representing the isolation material characteristics. The damping behavior is still treated linearly in that the damping coefficient is based on an experimentally determined, user-specified, damping ratio, treated as a material property. Thus, when the nonlinear isolation material option is selected, the stress-strain characteristics are nonlinear, while the stress-strain-rate characteristics remain linear.

WEDIM includes routines for assessing the potential for discomfort and injury from isolated shocks. The isolated shock analysis methods used in the model are based on the displacement-response method of Payne and Brinkley for seated occupants, and the acceleration-duration method of Glaister for seated or standing occupants. Prediction of discomfort and performance loss resulting from vibration, and vibration mixed with shock, is not presently included in WEDIM.

Application and Results

WEDIM was applied to a baseline HSPB with 10 seated human occupants. The purpose of the simulation was to provide a theoretical characterization of the water-entry acceleration time history to complement the at-sea accelerometer measurements and to relate the acceleration time history to potential for injury.

For the example simulation, the boat weighed 18,000 lb, and the 10 humans weighed a total of 2,000 lb. The boat and deck were treated as a rigid unit and dropped at level trim from a height of 8.0 ft to a calm water surface impacting at 22 ft/sec. The hull deadrise was 23 deg, with a chine beam of 8.2 ft and a waterline length of 29 ft. The sitting human was approximated as a linear spring-mass-damper system with a natural frequency of 52.9 rad/sec and a damping ratio of 0.224.

The predicted time histories of the initial impulsive added mass force and the buoyancy and drag forces are shown in Figure 15. The acceleration, velocity, and displacement time histories of the human, deck, and boat are shown in Figures 16, 17, and 18. The initial impact produces a maximum boat/deck acceleration of 7.3 g, and a maximum human acceleration of 9.5 g, as shown in Figure 18.

Figure 16 may be compared to Figure 7, the at-sea HSPB vertical acceleration time history. The measured data represent the far more complex problem of the full planing boat impacting complex waves in a seaway, while the prediction corresponds to a 29-ft, 2-D wedge falling onto calm water. However, the time histories are remarkably similar. The magnitude of the measured acceleration is approximately 6 g, while the predicted magnitude is 7.3 g. The duration of the measured water-entry impact is approximately 70 msec, comparable to that of the prediction (at the 2.5 g level).

A portion of Figure 18 is enlarged in Figure 19 to illustrate the displacement-response method. The values calculated in WEDIM are listed in Table 3. The maximum displacement between the deck and the seated human CG, 0.13 ft, occurs at 0.765 sec into the water-impact time history. This value is nondimensionalized according to Equation (2), to form a DRI value of 10.1. A figure of merit may be constructed as the ratio of this DRI value and the training DRI level of 15.2 in Table 3. The resulting figure of merit for the seated occupants of the HSPB is thus 0.66.

Since a DRI model of the standing human is not available, the acceleration-duration method is used for standing occupants. The acceleration of the deck was shown in Figure 16. The acceleration-duration method of Glaister assumes the motion of the platform on which the humans are standing is unaffected by the presence of the humans. This assumption is reasonable, given the 2000-lb weight of the humans relative to the 18,000-lb weight of the hull and deck. The equivalent duration of the maximum hull/deck acceleration of 7.3 g was computed as 0.062 sec. The acceleration duration is plotted on Glaister's curves in Figure 20. A figure of merit may be constructed as the ratio of the maximum acceleration to the maximum tolerable acceleration at the given duration. For a seated occupant, the maximum tolerable acceleration is 7.8 g, so the figure of merit is 0.93. These results and those for the standing occupants are summarized in Table 4.

The guidelines of Glaister, which represent contours of *maximum tolerable impact loading* may be considered as comparable to the tolerable training levels defined by Brinkley as the 0.5 percent injury rate for U.S. Air Force (USAF) seat ejection training listed in Table 1. The figures of merit computed for the two methods, 0.67 and 0.93, are comparable given the highly approximate nature of the methods and discomfort/injury characteristics.

CSS PLANING BOAT MODEL

CSS developed the semi-empirical Planing Boat Model in an effort to predict the shock mitigating effects of variations in hull geometry. The empirical equations and resulting computer model are limited in their ability to address both severe slam conditions and innovative candidate geometries.

Description

Savitsky[61] developed a semi-empirical method for predicting the resistance of hard chine planing hulls in calm water. Later Savitsky and Brown[20] extended the methods of Reference 61 by developing empirical equations to estimate the additional resistance and the heave accelerations during planing in a seaway. The Savitsky-Brown seaway equations are based on the seakeeping model test data of Fridsma.[18,19] These data were obtained for a family of captive models in a seakeeping test in irregular seas in the Davidson Laboratory of the Stevens Institute of Technology, Hoboken, NJ. The semi-empirical Planing Boat Model reproduces the calm-water and rough-water resistance and acceleration data of References 18, 19, 20, and 61.

The calm-water resistance predictions of the Planing Boat Model are accurate for many planing boat geometries and conditions. However, the shock mitigation effort includes hull shapes beyond the conventional geometries of the Fridsma series. Further, the Fridsma test series included only moderately rough sea conditions because, in general, small planing boat operators slow down to avoid severe slams as the sea conditions deteriorate. Conventional seakeeping model series tests would require extensive redesign to characterize repeated slams. The redesign must address higher strength models and model support systems and faster data acquisition to accommodate the higher frequencies and magnitudes of the impulsive loads.

The Planing Boat Model assumes a constant deadrise, hard-chine hull. If the hull geometry varies longitudinally along the planing surface, a reasonable approximation may be obtained with or average deadrise and beam values in the planing region. The code requires:

- Shaft angle relative to the keel
- Vertical separation between the propeller shaft and the CG
- Vertical distance from the keel to the CG
- Longitudinal distance from the lower edge of the transom to the CG
- Nominal deadrise angle and beam in the planing region of the hull
- At-rest length on the waterline
- Total displaced weight
- Significant wave height
- Boat speed

The code then computes the:

- Calm-water resistance and effective power
- Rough-water added resistance
- Rough-water added effective power
- Rough-water heave accelerations at the CG
- Rough-water heave accelerations at the bow

Predictions include the average, the 1/3rd highest, and the 1/10th highest accelerations. The permissible ranges of speeds and wave heights within the model correspond to conditions for which the hull remains largely in the water and rarely slams.

Application and Results

Table 5 summarizes the boat geometry corresponding to the HSPB simulated with WEDIM. The significant wave height and speed values are constrained to be within the bounds of the data on which the empirical code is based. The geometric parameter varied in the analysis was deadrise angle. The goal was to examine the classic trade-off between powering performance and ride quality for varying deadrise.

Figure 21 summarizes the results of the power/impact trade-off analysis. As expected, the 1/10th highest heave accelerations at the CG are reduced for increasing deadrise angle. An angle of 14 deg produces a 1/10th highest acceleration value of 5.5 g, while at 32 deg, the acceleration is reduced to 3.0 g. The calm-water effective power increases by 22 percent, from 239 to 292 hp, over the range of deadrise angle. However, the rough-water effective power remains essentially unchanged for increasing deadrise angle. For higher deadrise angles, the increased wetted area increases the requirement for power, while the reduced pitch and heave motions lower the requirement, resulting in a net change of nearly zero.

RECOMMENDATIONS

The at-sea acceleration tests conducted to date have served to identify typical exposures of HSPBs and their occupants to repeated shock and to determine fundamental frequency components of the shocks. The data are limited to certain platforms, sea states, and speeds. Additional testing is needed to characterize all appropriate platforms through complete ranges of speeds and sea states. A more complete test matrix would also include variations of other parameters such as boat weights, payloads, and CGs and buoyancy. Additional testing should be conducted to correlate operator perceptions and injuries to measured and recorded data describing the operational environment and boat accelerations.

Accurate measurements of the initial water-entry impact accelerations can be made with piezoelectric accelerometers. Piezoresistive accelerometers generally provide better low-frequency response than piezoelectric accelerometers for measurement of the recovery phase of

planing boat impacts. Investigators should determine the combined time constant of the accelerometers and the data collection and storage equipment to ensure correct interpretation of the collected data.

Historically, consistent and repeatable data concerning repeated shocks have been difficult to obtain. Few studies have been conducted, and the data were collected with different instrumentation, filtering frequencies, and sample rates onboard different platforms. Accelerations reported for the same platforms can vary. The seaway is difficult to quantify and repeat. Results can vary according to boat configuration, boat crew experience, and measurement and analysis techniques. Low-pass filtering is often used to help separate repeated shocks from background vibration, but filtering methods or levels are often not reported. Efforts to ensure repeatability and complete reporting are recommended.

Development of a suitable planing boat dynamics simulation is vital for cost-effective, long-term shock mitigation research. The code should include the ability to simulate an elastic hull with prescribed shock isolation components, innovative hull geometries, and human dynamics and injury. Drop tests are recommended for calibrating and validating the water-impact theory within the simulation.

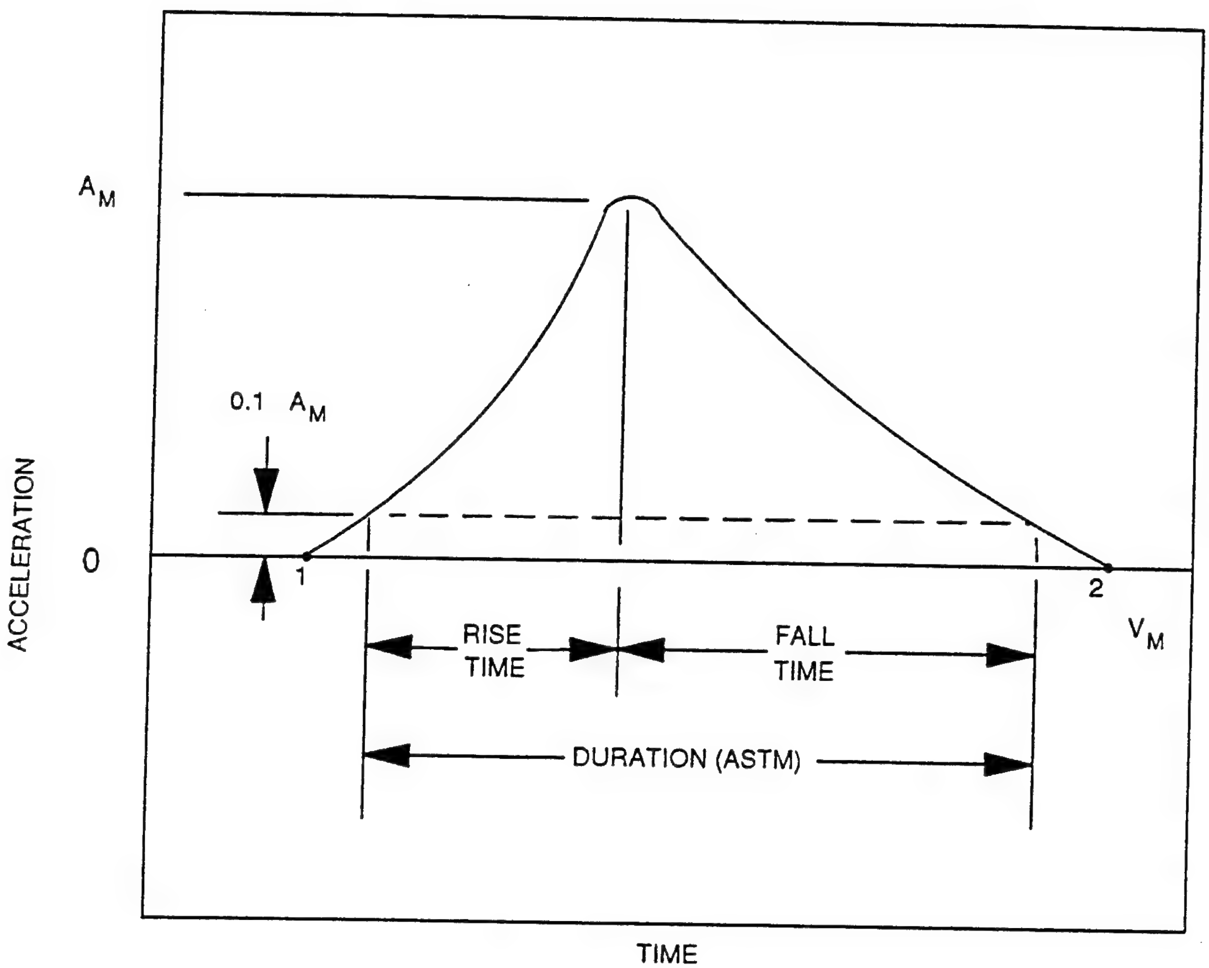

FIGURE 1. TERMS USED TO CHARACTERIZE SHOCKS

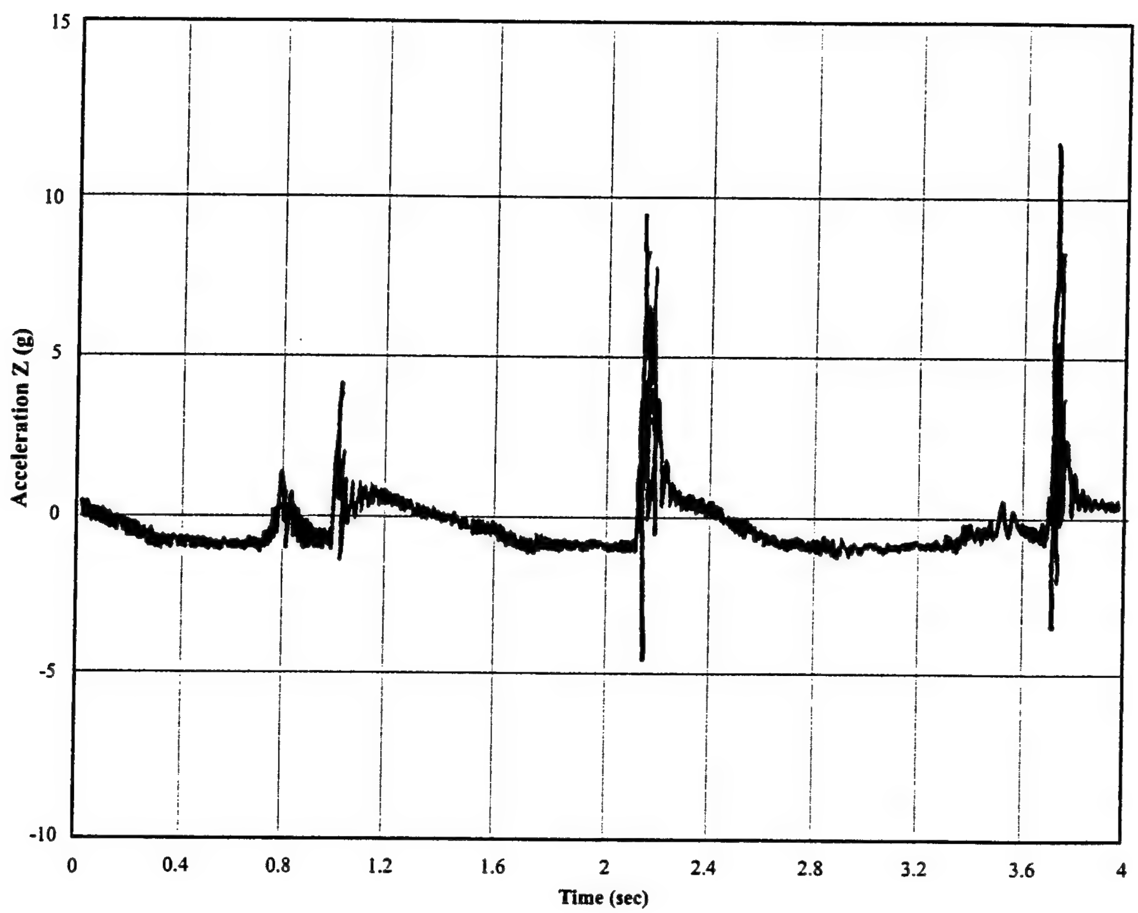

FIGURE 2. UNFILTERED ACCELERATION TIME HISTORY MEASURED WITH PIEZORESISTIVE ACCELEROMETER

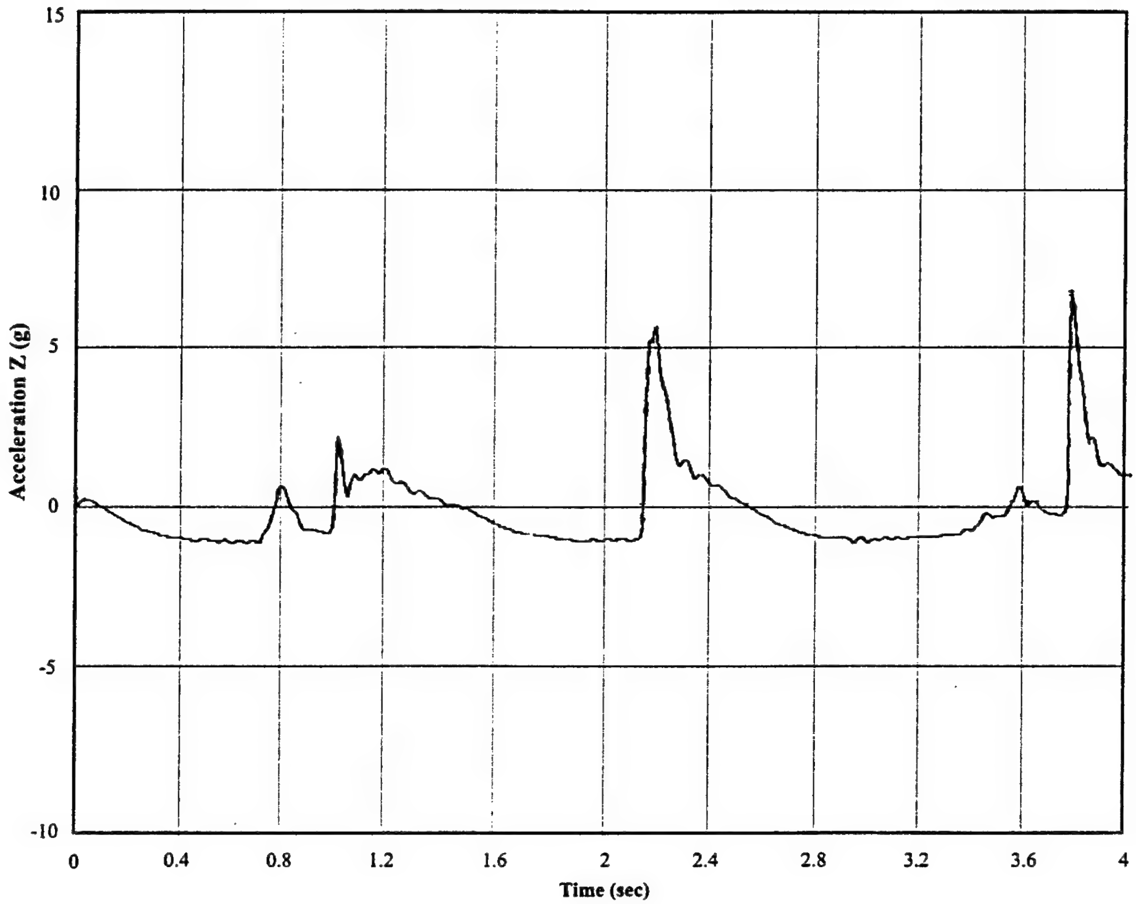

FIGURE 3. ACCELERATION TIME HISTORY MEASURED WITH PIEZORESISTIVE ACCELEROMETER, FILTERED AT 25 Hz

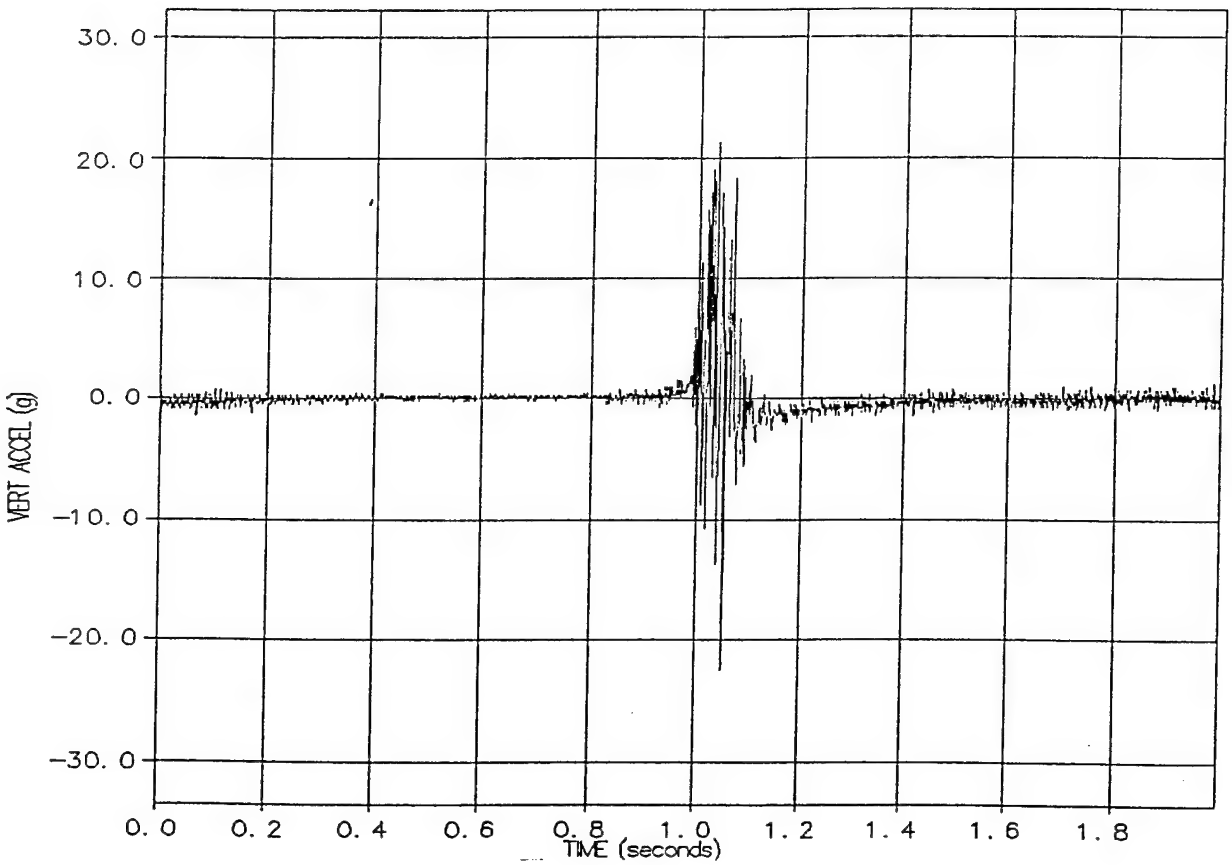

FIGURE 4. UNFILTERED ACCELERATION TIME HISTORY MEASURED WITH PIEZOELECTRIC ACCELEROMETER

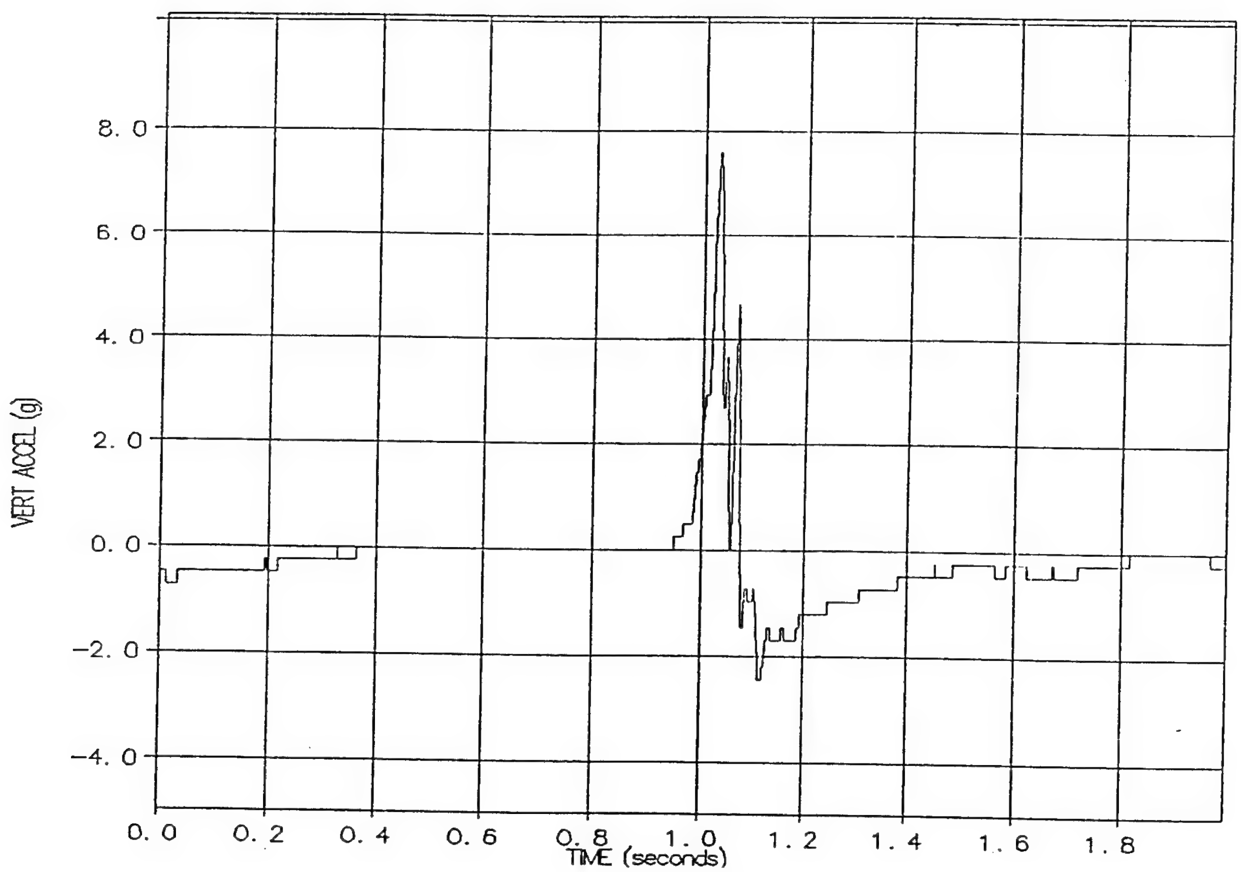

FIGURE 5. ACCELERATION TIME HISTORY MEASURED WITH PIEZOELECTRIC ACCELEROMETER, FILTERED AT 100 Hz

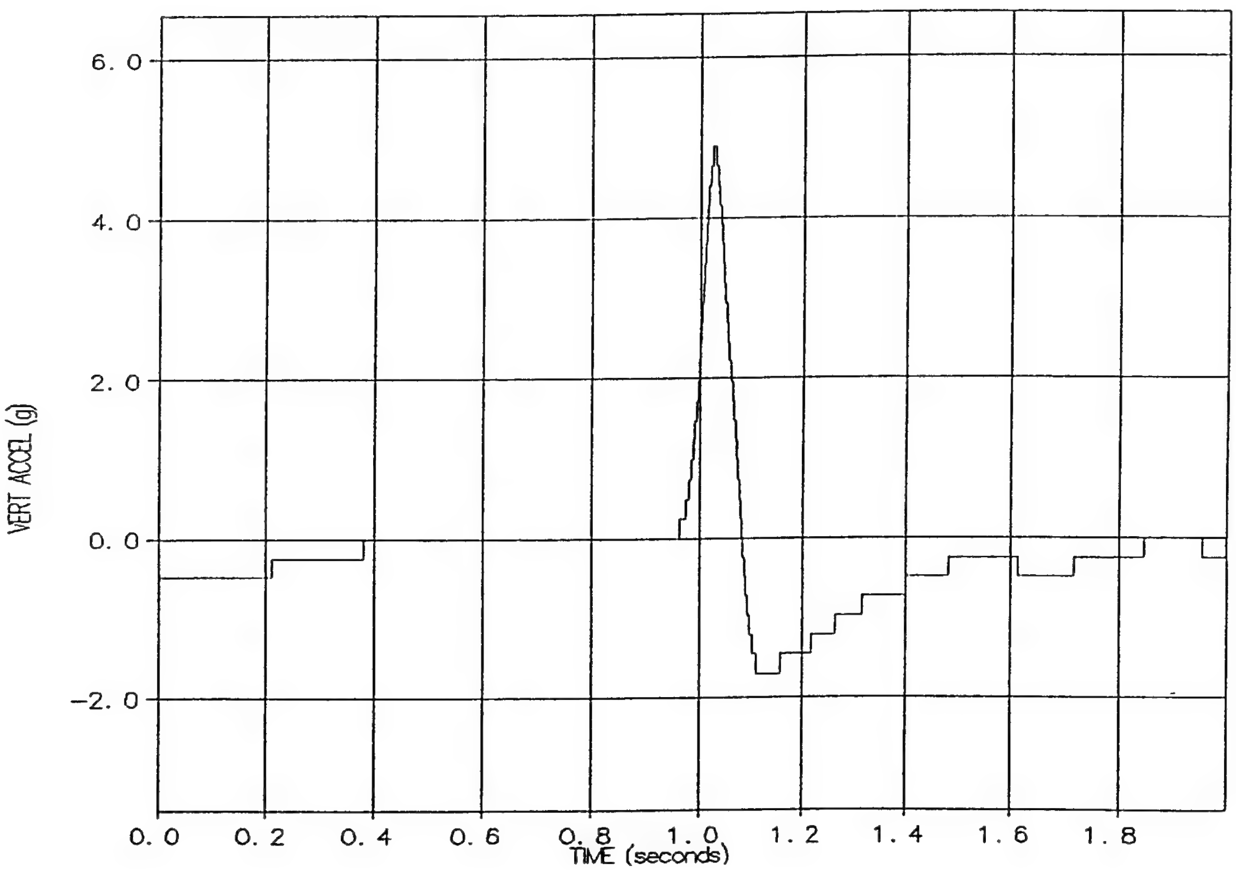

FIGURE 6. ACCELERATION TIME HISTORY MEASURED WITH PIEZOELECTRIC ACCELEROMETER, FILTERED AT 30 Hz

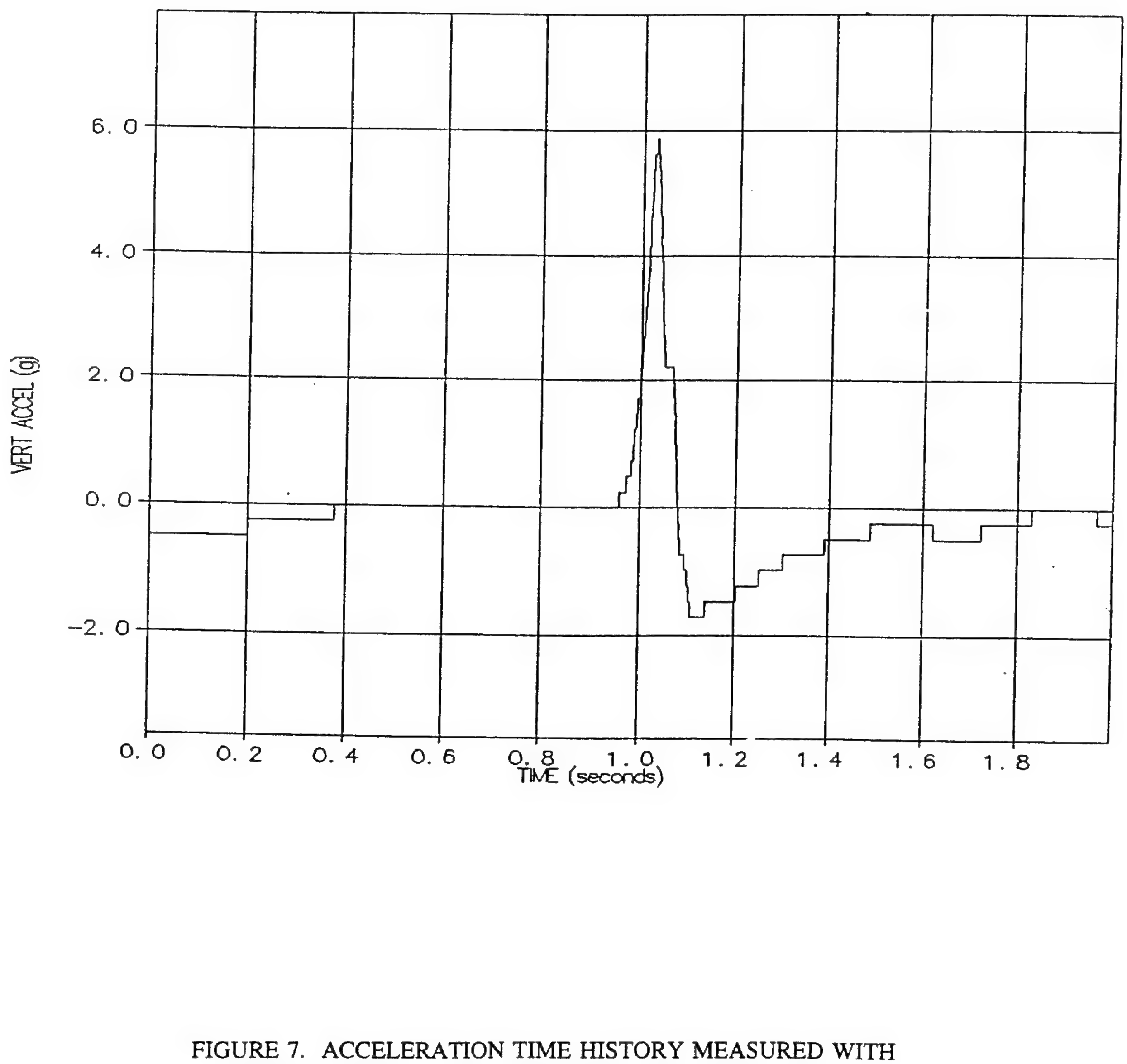

FIGURE 7. ACCELERATION TIME HISTORY MEASURED WITH PIEZOELECTRIC ACCELEROMETER, FILTERED AT 50 Hz

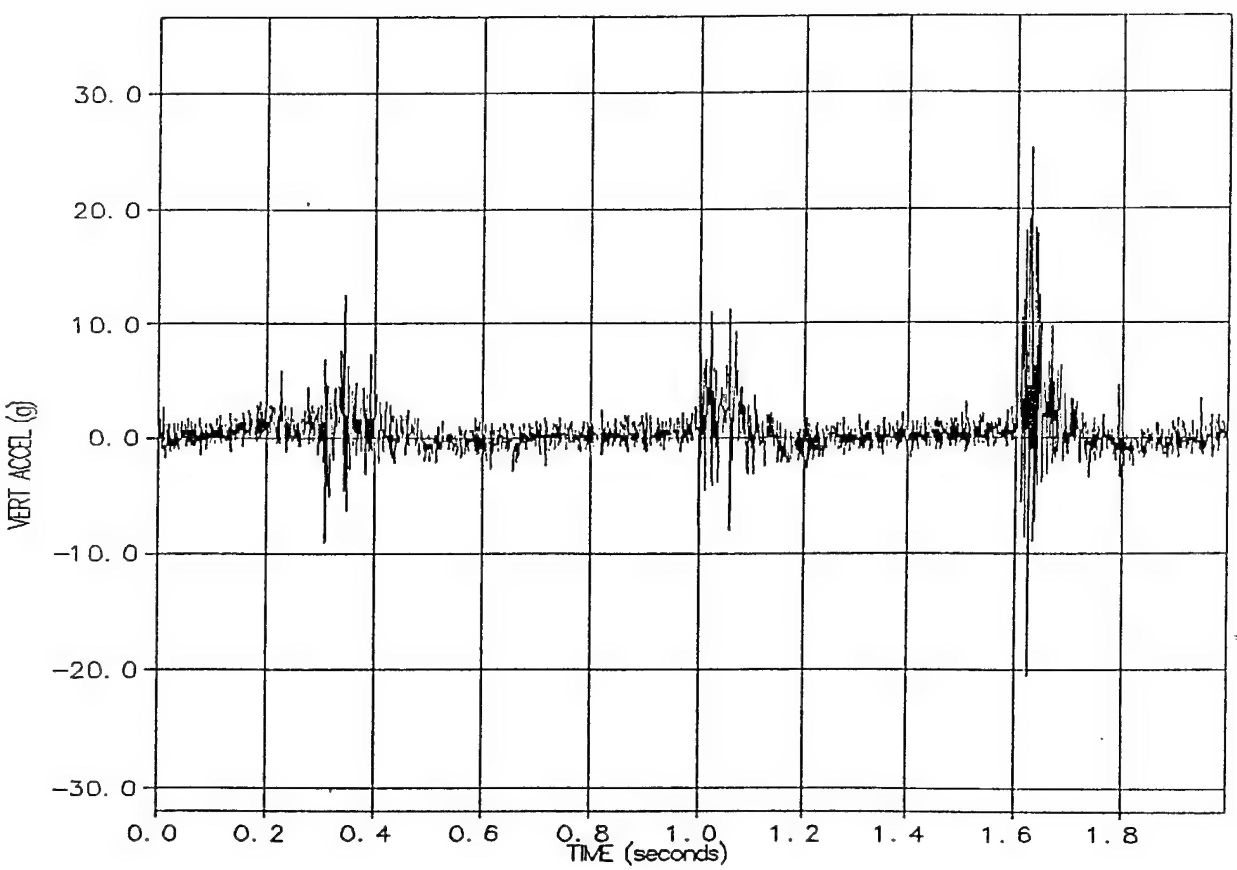

FIGURE 8. UNFILTERED ACCELERATION TIME HISTORY OF MULTIPLE EVENTS MEASURED WITH PIEZOELECTRIC ACCELEROMETERS

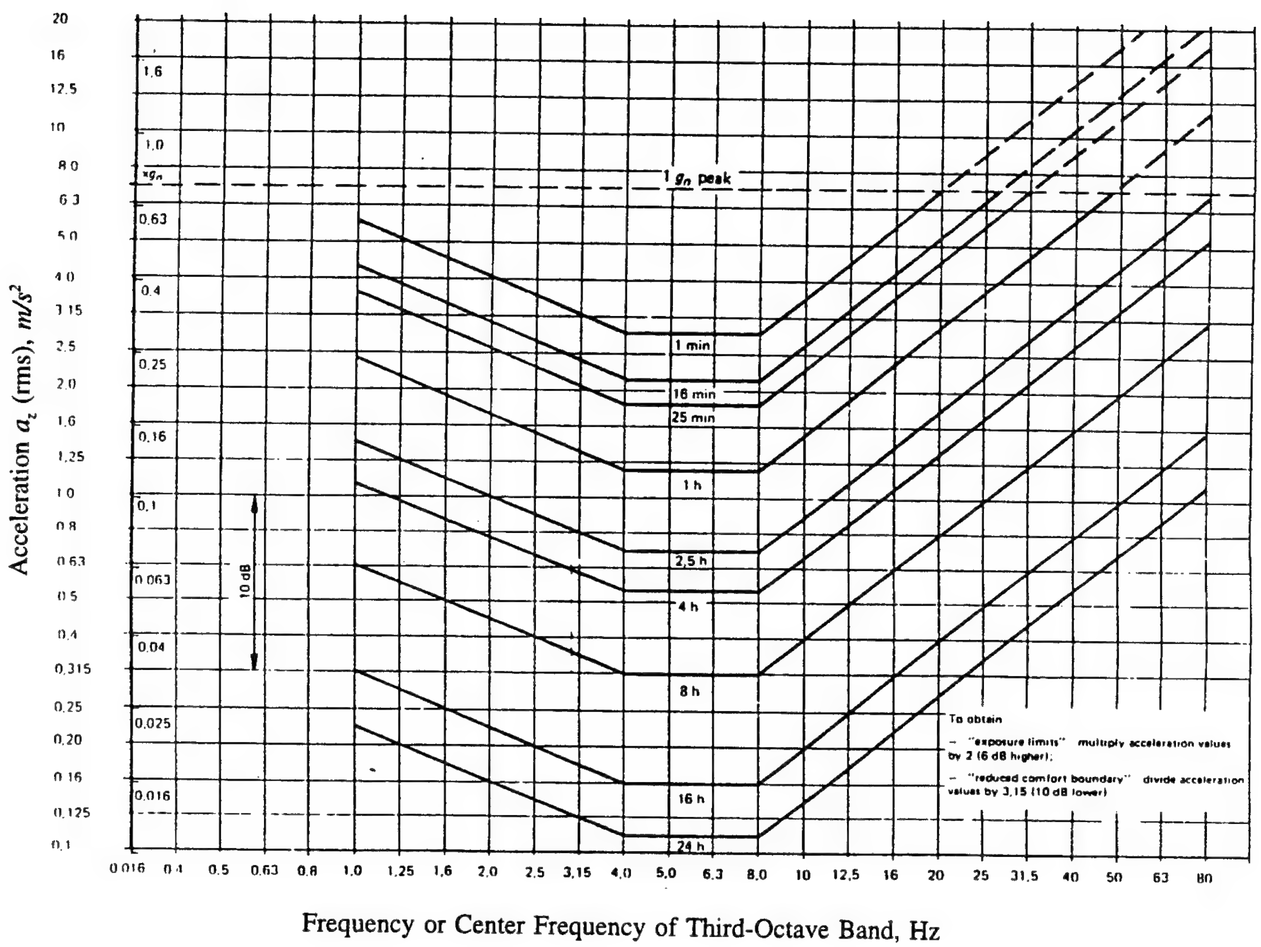

FIGURE 9. VIBRATION EXPOSURE CRITERIA FOR VERTICAL DIRECTION

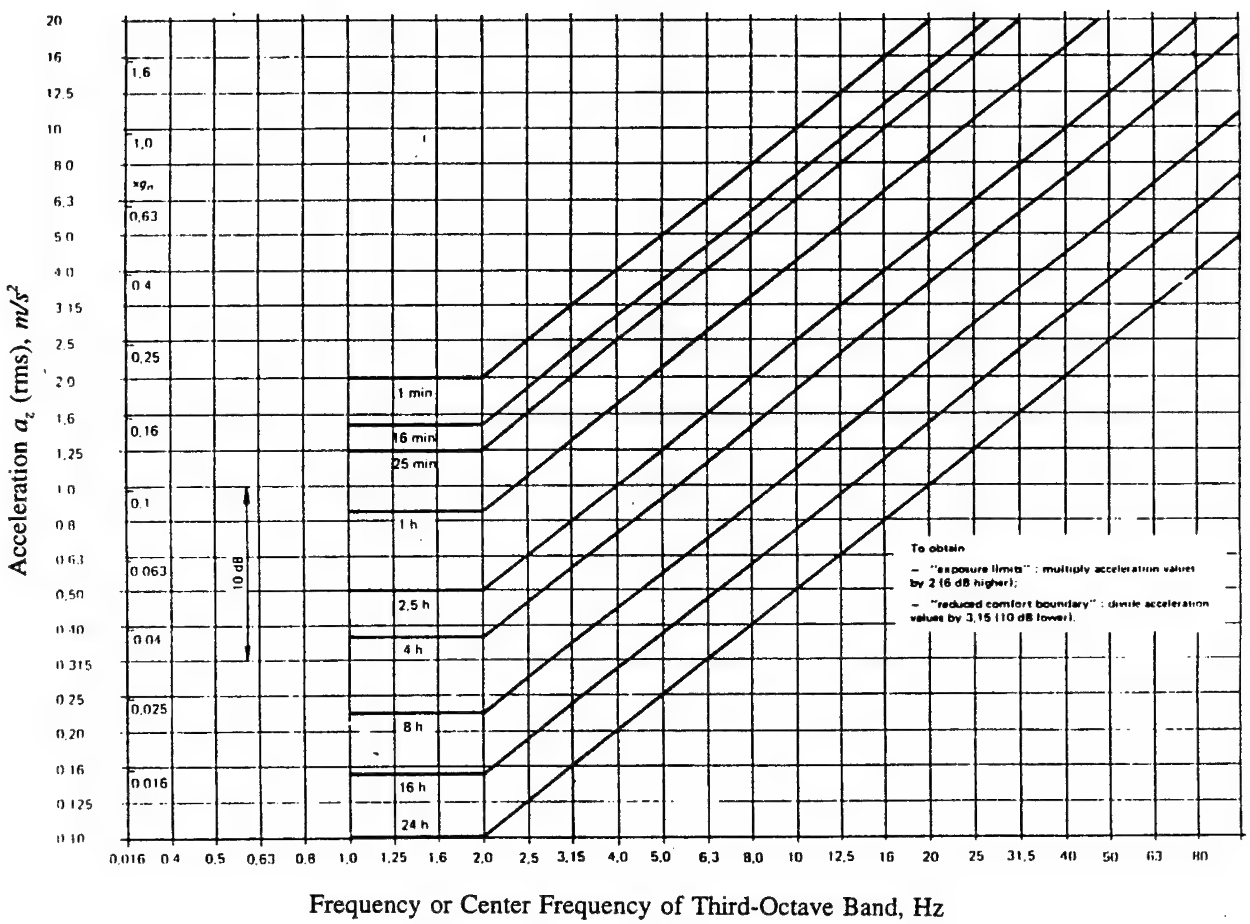

FIGURE 10. VIBRATION EXPOSURE CRITERIA FOR LATERAL DIRECTION

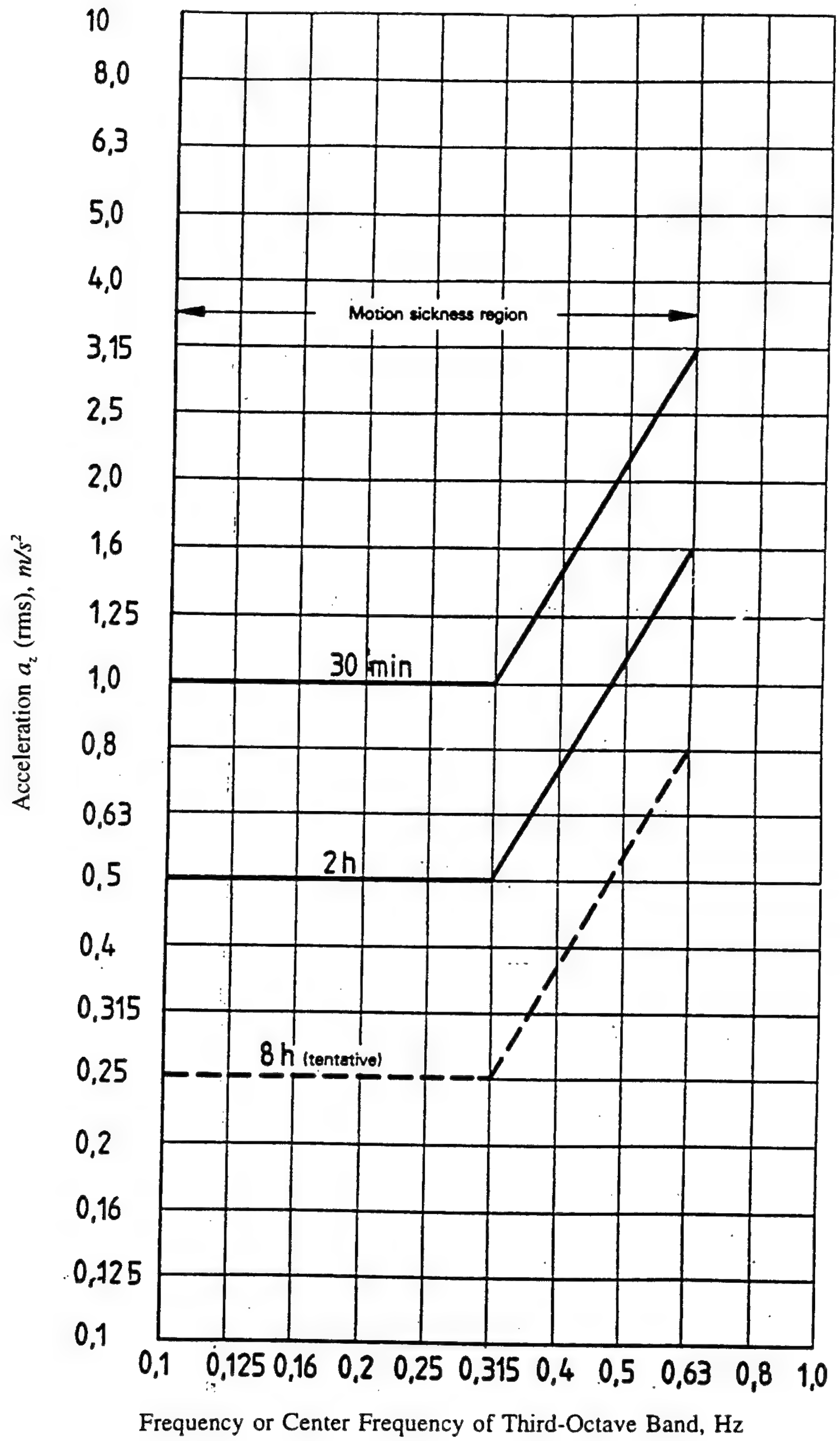

FIGURE 11. VIBRATION EXPOSURE CRITERIA FOR LOW FREQUENCY

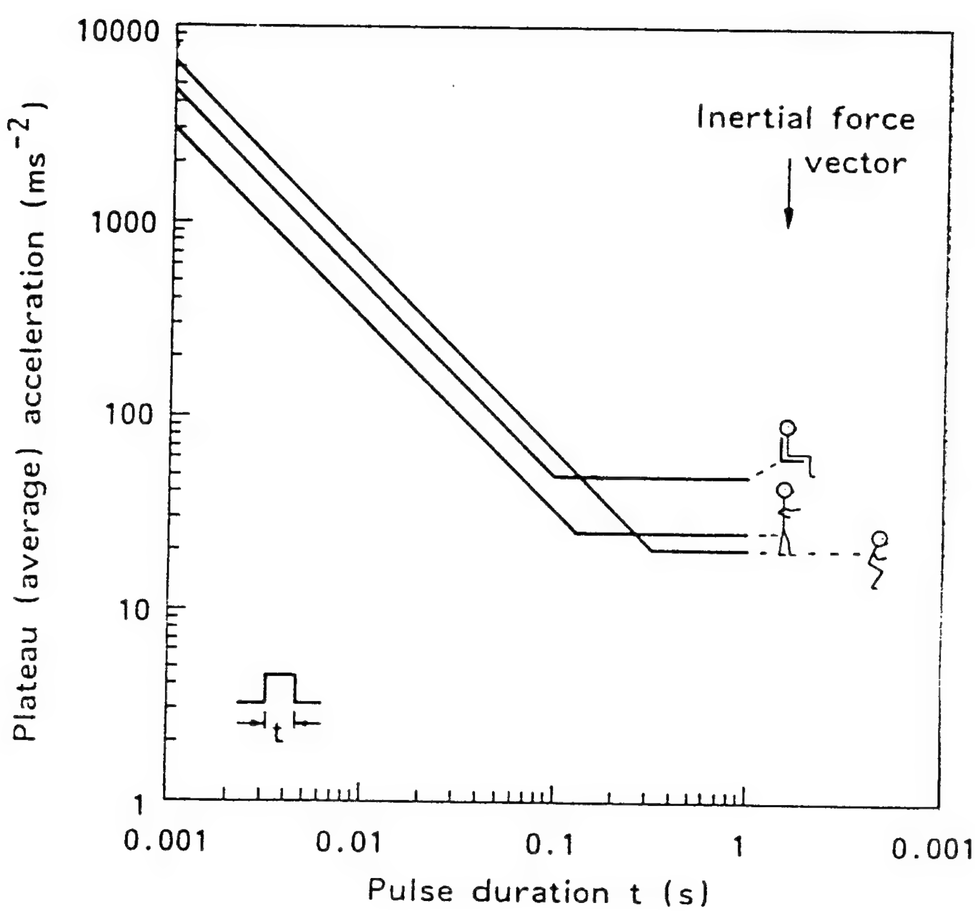

FIGURE 12. TOLERABLE PLATFORM ACCELERATION-DURATION LEVELS

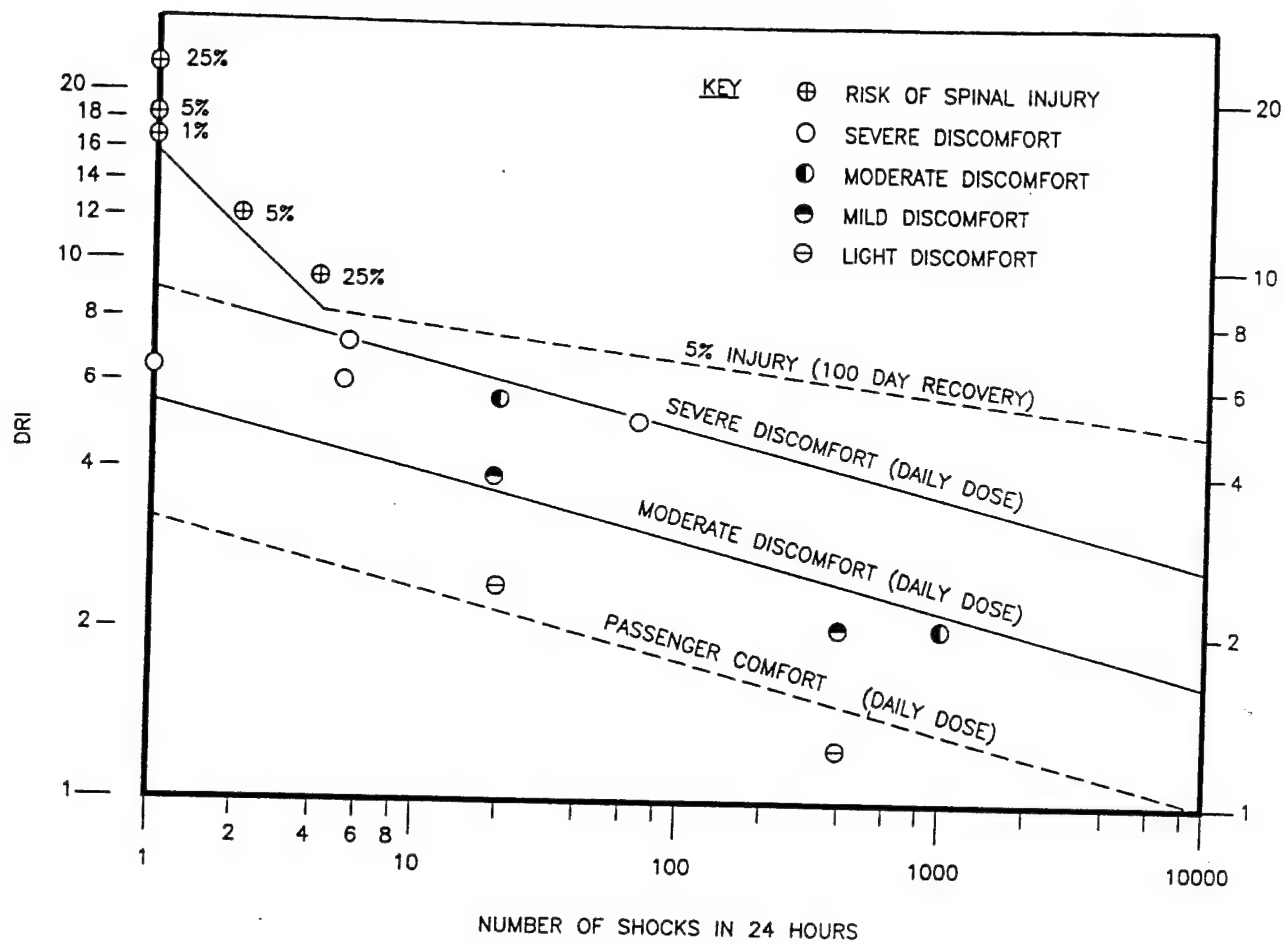

FIGURE 13. TOLERANCE LIMITS FOR EXPOSURE TO REPEATED DRIs

$$M_h \ddot{Z}_h = C_h (\dot{Z}_d - \dot{Z}_h) + K_h (Z_d - Z_h) - F_{hg}$$

$$M_d \ddot{Z}_d = C_h (\dot{Z}_h - \dot{Z}_d) + K_h (Z_h - Z_d) + C_i (\dot{Z}_b - \dot{Z}_d) + K_i (Z_b - Z_d) - F_{dg}$$

$$M_b \ddot{Z}_b = C_i (\dot{Z}_d - \dot{Z}_b) + K_i (Z_d - Z_b) - F_{bg} + F_w$$

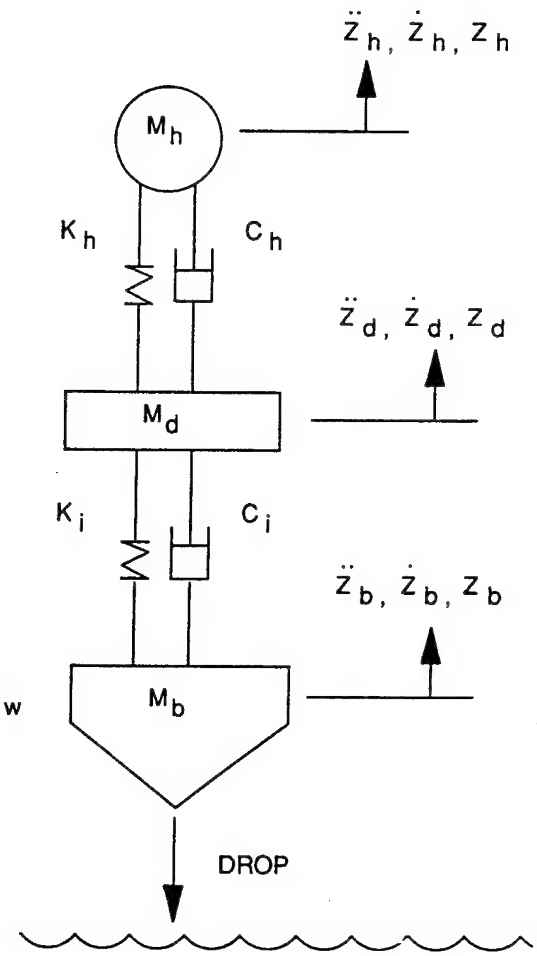

FIGURE 14. EQUATIONS OF MOTION FOR THREE DOF SIMULATION

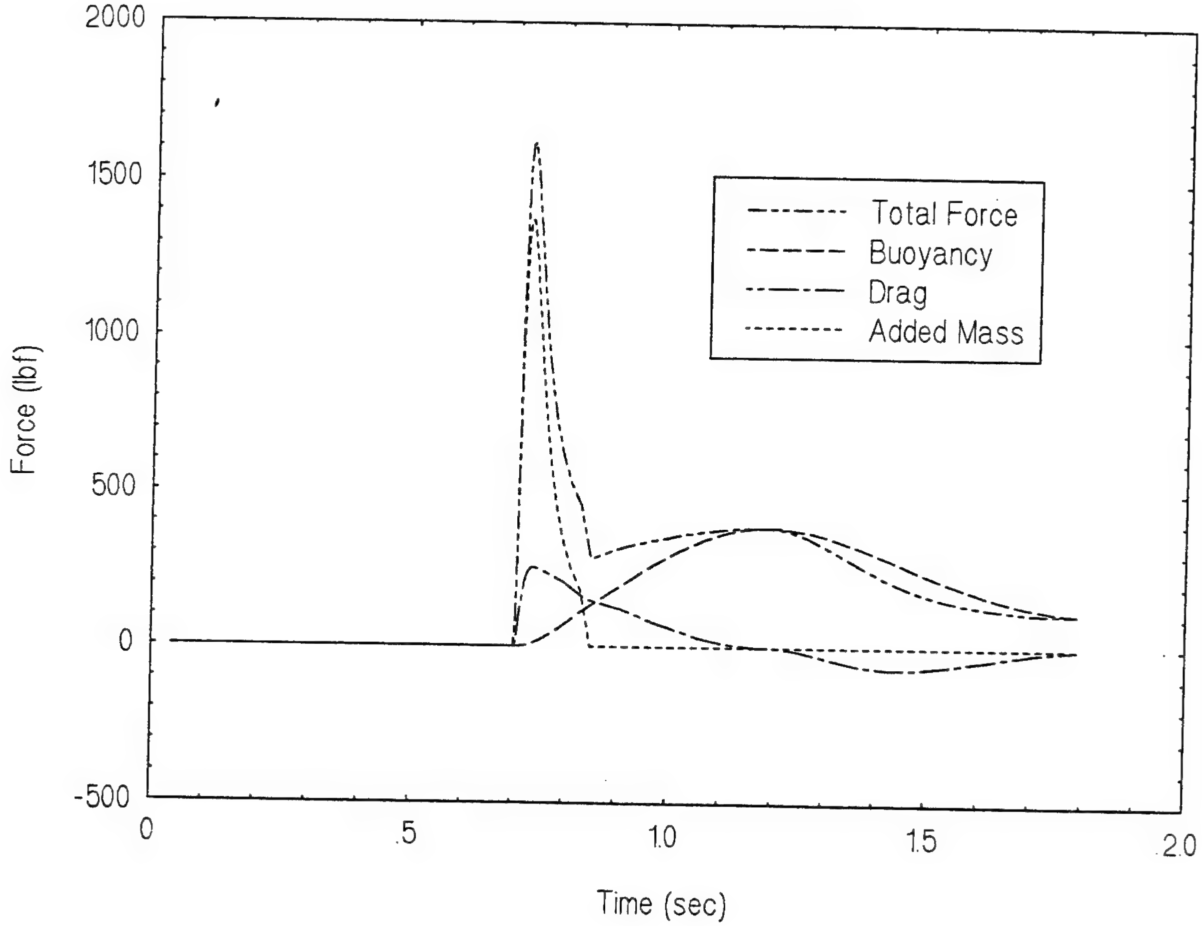

FIGURE 15. FORCE COMPOSITION, HSPB 8-FT DROP, WEDIM PREDICTION

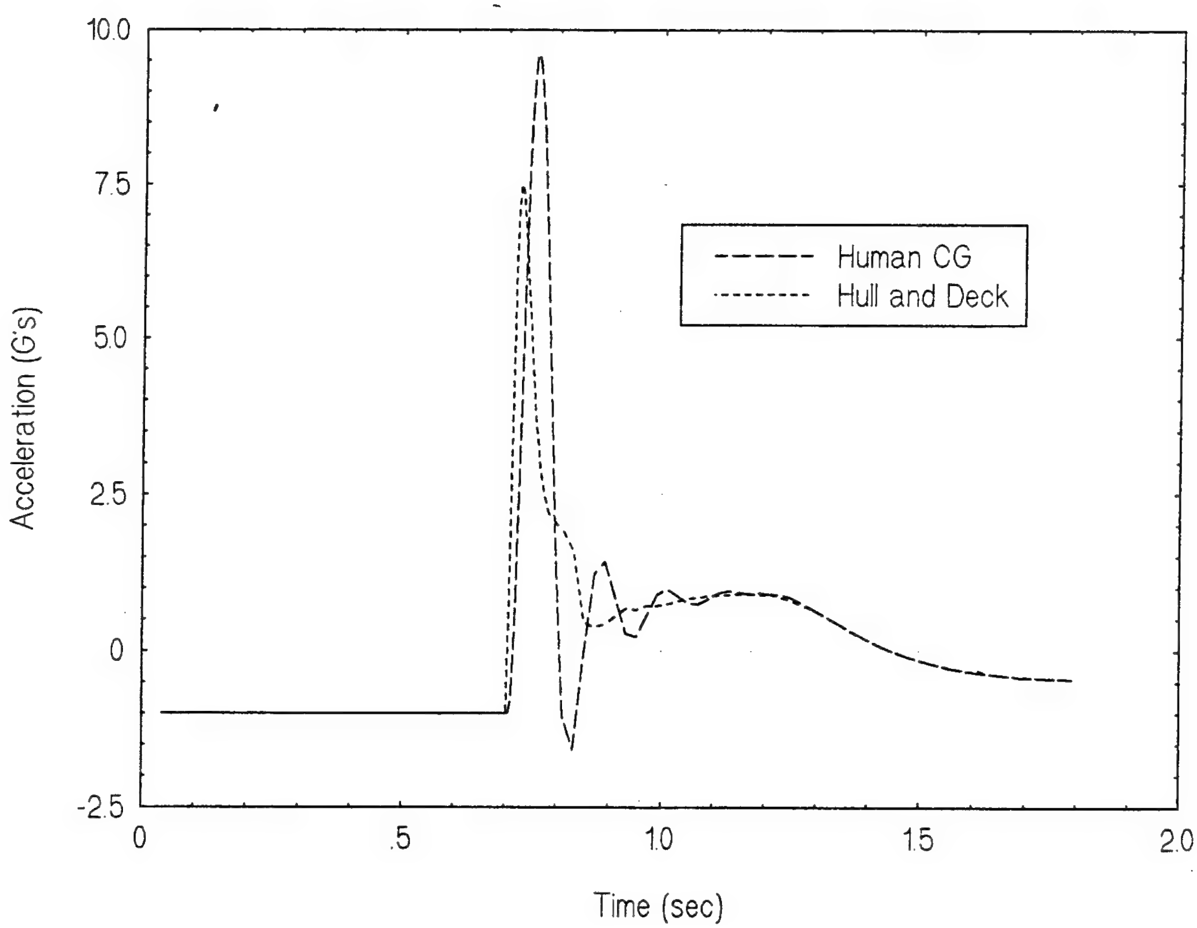

FIGURE 16. ACCELERATIONS, HSPB 8-FT DROP, WEDIM PREDICTION

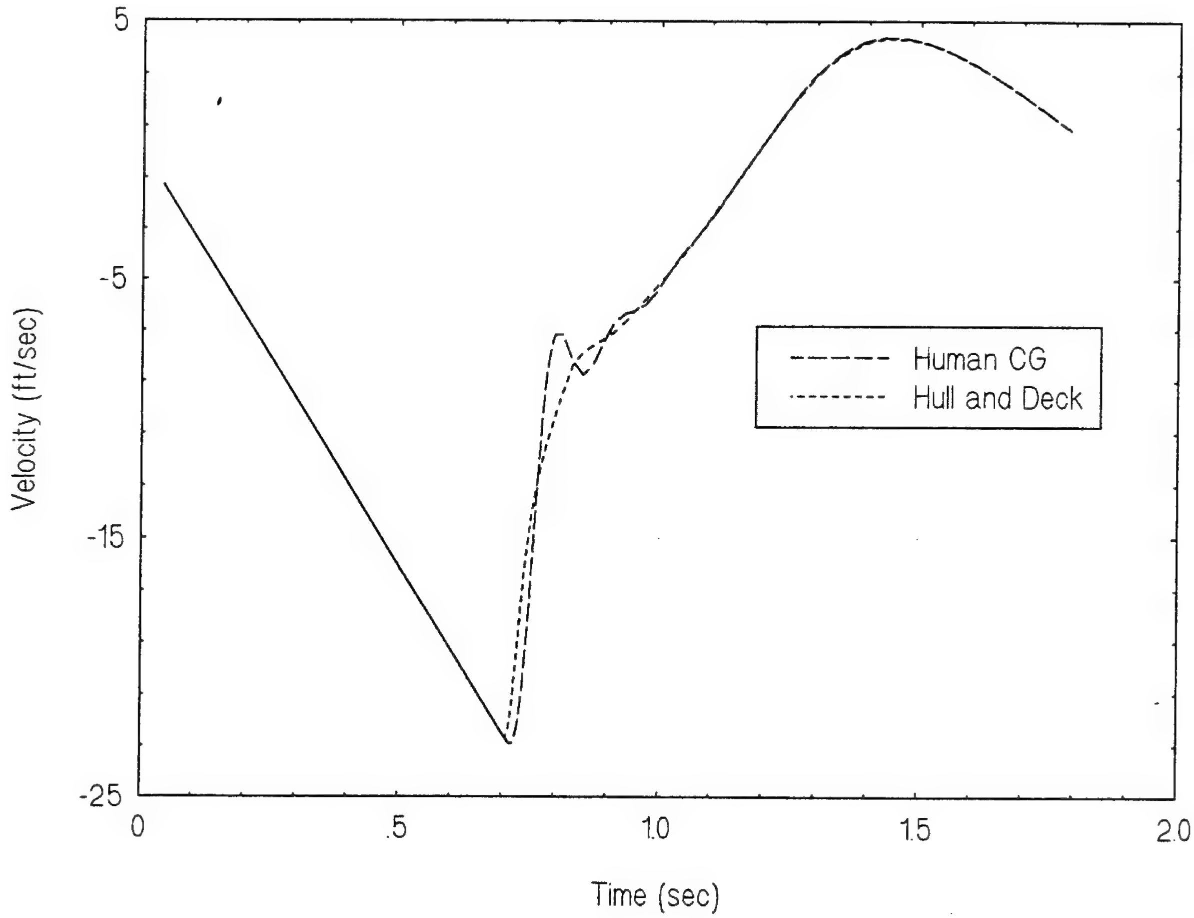

FIGURE 17. VELOCITIES, HSPB 8-FT DROP, WEDIM PREDICTION

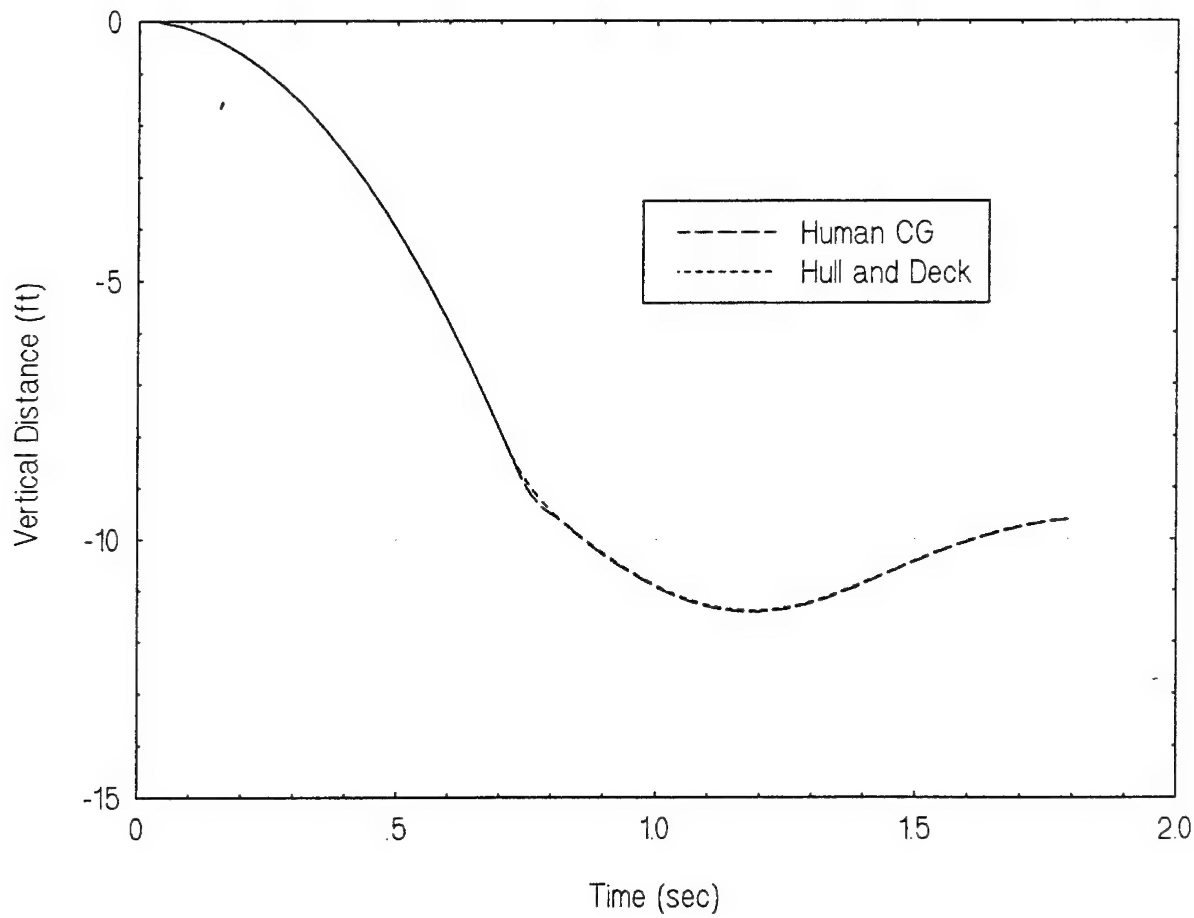

FIGURE 18. DISPLACEMENTS, HSPB 8-FT DROP, WEDIM PREDICTION

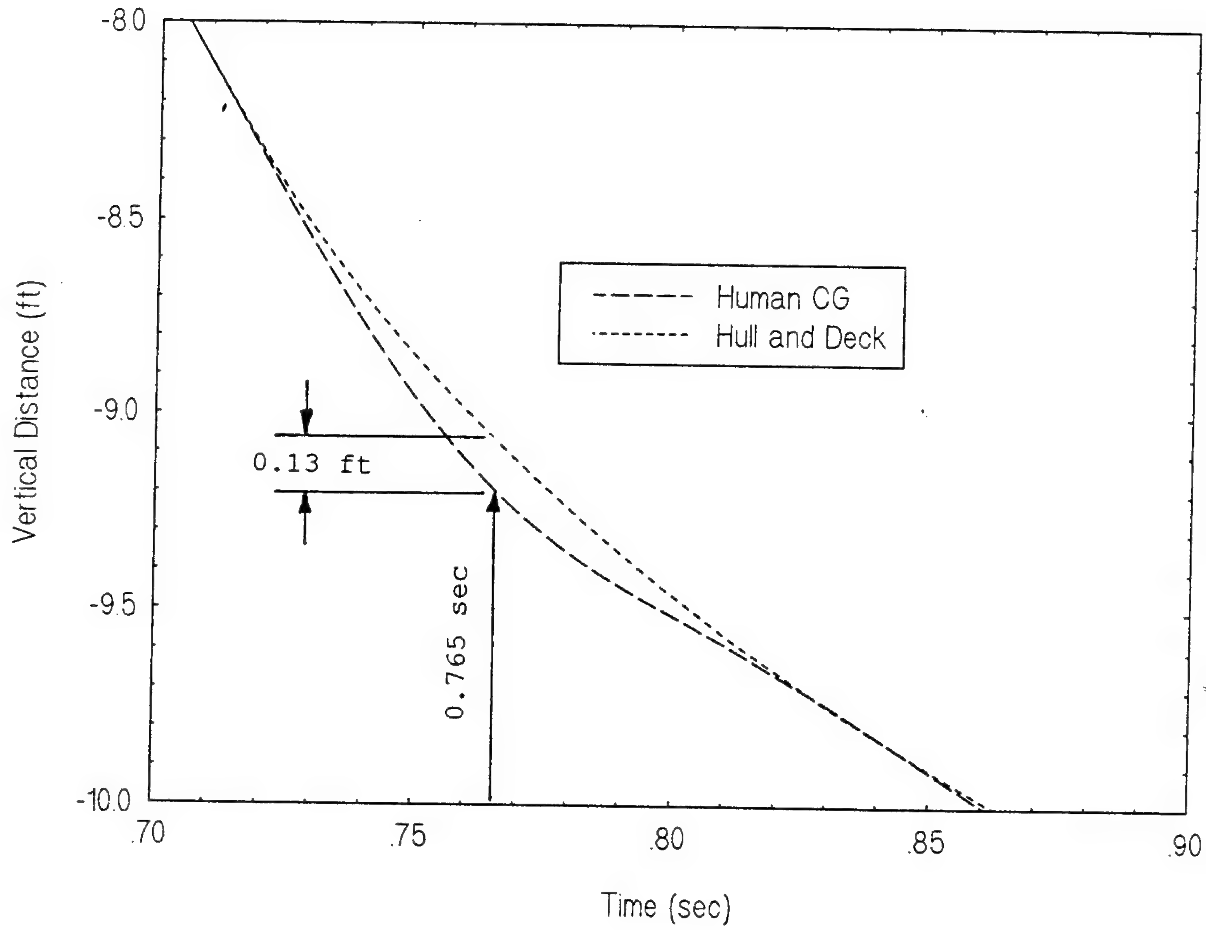

FIGURE 19. DISPLACEMENT-RESPONSE INJURY ASSESSMENT, HSPB 8-FT DROP, WEDIM PREDICTION

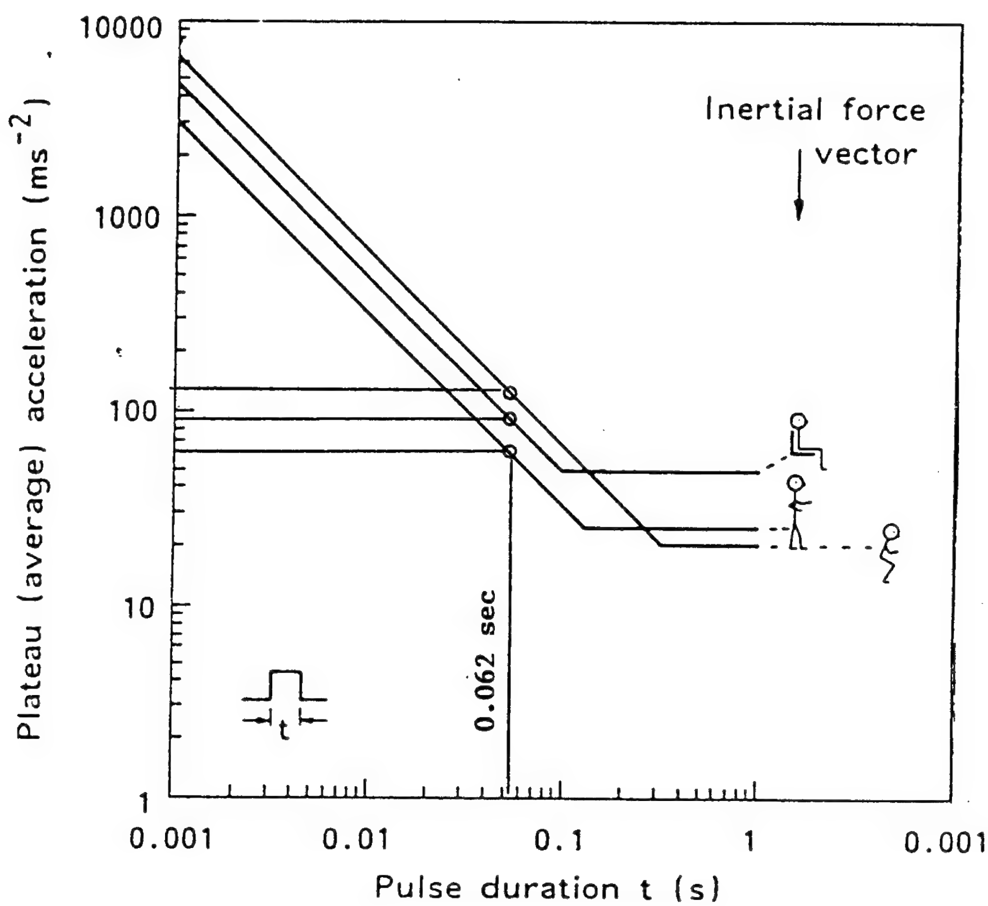

FIGURE 20. ACCELERATION-DURATION INJURY ASSESSMENT, HSPB 8-FT DROP, WEDIM PREDICTION

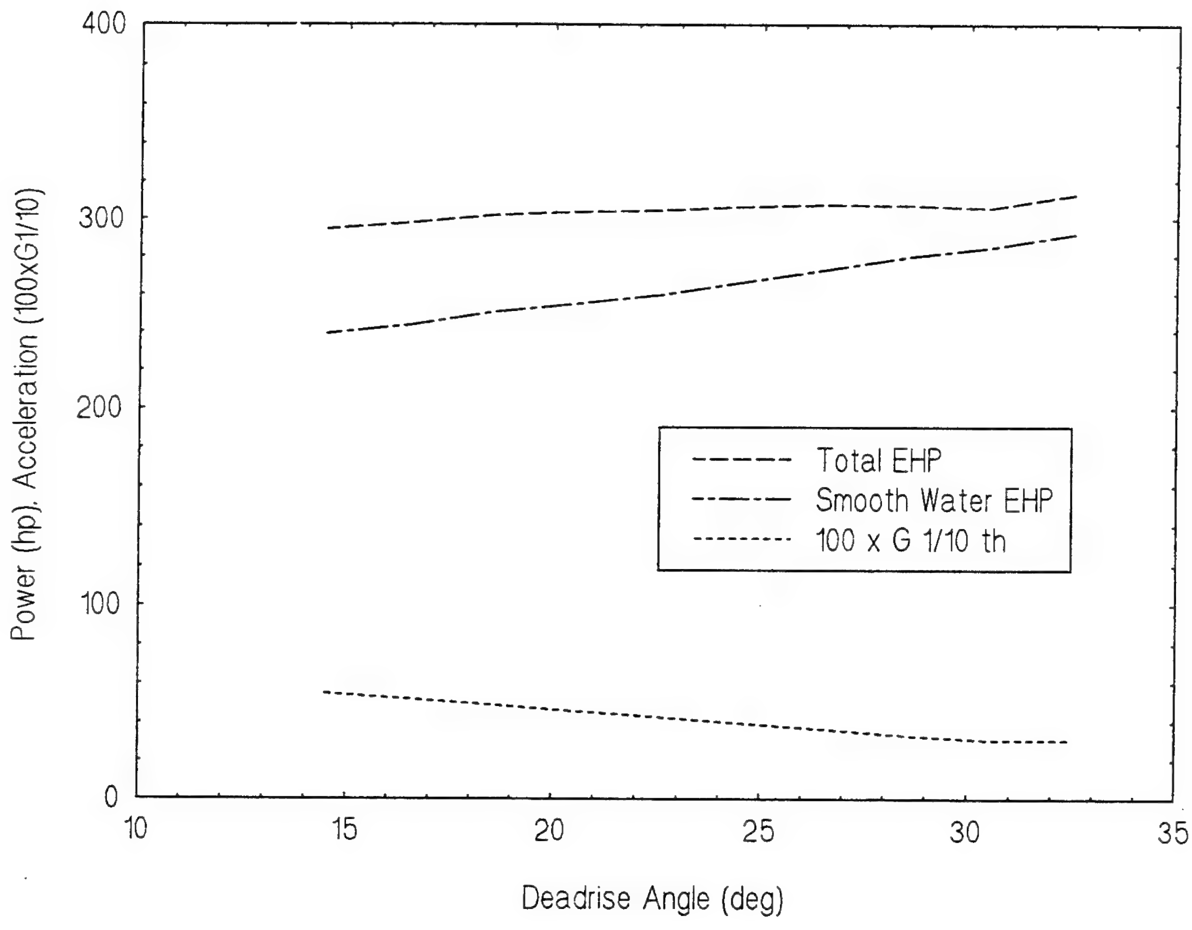

FIGURE 21. DEADRISE/POWER TRADEOFF, HSPB MODEL PREDICTION

TABLE 1. VERTICAL, SEATED HUMAN DRI GUIDELINES

DESIGNATION	APPLICATION	PERCENT PROBABILITY OF SPINAL INJURY	DRI VALUE
Low	USAF Seat Ejection Training	0.5	15.2
Moderate	USAF Ejection Seat Design	5.0	18.0
High	Observed USAF Ejections	50.0	22.0

TABLE 2. PARAMETERS OF BODY-SEAT MODEL

DIRECTION	NATURAL FREQUENCY (rad/sec)	BODY MASS (slugs)	STIFFNESS (lbs/ft)	DAMPING (slugs/sec)	DAMPING RATIO
X (eyes in/out)	62.8	5.14	2.06E4	64.6	0.100
Y (eyes lft/rt)	58.0	5.14	1.71E6	53.7	0.090
Z (eyes down)	52.9	5.14	1.44E4	121.8	0.224

TABLE 3. DRI INJURY ASSESSMENT FOR 8-FT HSPB DROP

PARAMETER	VALUE
Maximum Displacement	0.130 ft
Displacement Response Index	10.0
Maximum Permissible DRI (Low Risk)	15.2
Ratio, Actual-to-Permissible	0.66

TABLE 4. PLATFORM INJURY ASSESSMENT FOR 8-FT HSPB DROP

PARAMETER	VALUE
Maximum Acceleration Equivalent Acceleration Duration	7.30 g 0.062 sec
Maximum Permissible Sitting Ratio, Actual-to-Permissible	7.80 g 0.93
Maximum Permissible Standing, Bent Ratio, Actual-to-Permissible	10.14 g 0.72
Maximum Permissible Standing, Straight Ratio, Actual-to-Permissible	5.31 g 1.37

TABLE 5. HSPB GEOMETRY AND CONDITIONS

GEOMETRY	VALUE
Shaft angle relative to keel	0.0 deg
Distance from shaft line to CG	2.7 ft
Distance from keel to CG	3.1 ft
Distance from transom to CG	10.0 ft
Nominal beam in planing region	8.2 ft
Length on waterline	29.0 ft
Boat weight, fully loaded	19,000 lb
CONDITIONS	**VALUE**
Speed	21 kt
Sea State (significant wave height)	5.5 ft

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